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Kirleis et al.

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(54) **PROGRAMMABLE BATTERY PACK**

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(73) Assignee: **Aurora Flight Sciences Corporation**, Manassas, VA (US)

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B64D 27/24 (2006.01)
B64D 27/26 (2006.01)
H01M 50/20 (2021.01)

(52) **U.S. Cl.**

CPC ***H02J 7/35*** (2013.01); ***B64D 27/24*** (2013.01); ***B64D 27/26*** (2013.01); ***H01M 50/20*** (2021.01); *B64D 2211/00* (2013.01)

(58) **Field of Classification Search**

CPC H02J 7/35; H01M 50/20; B64D 27/24; B64D 27/26; B64D 2211/00

See application file for complete search history.

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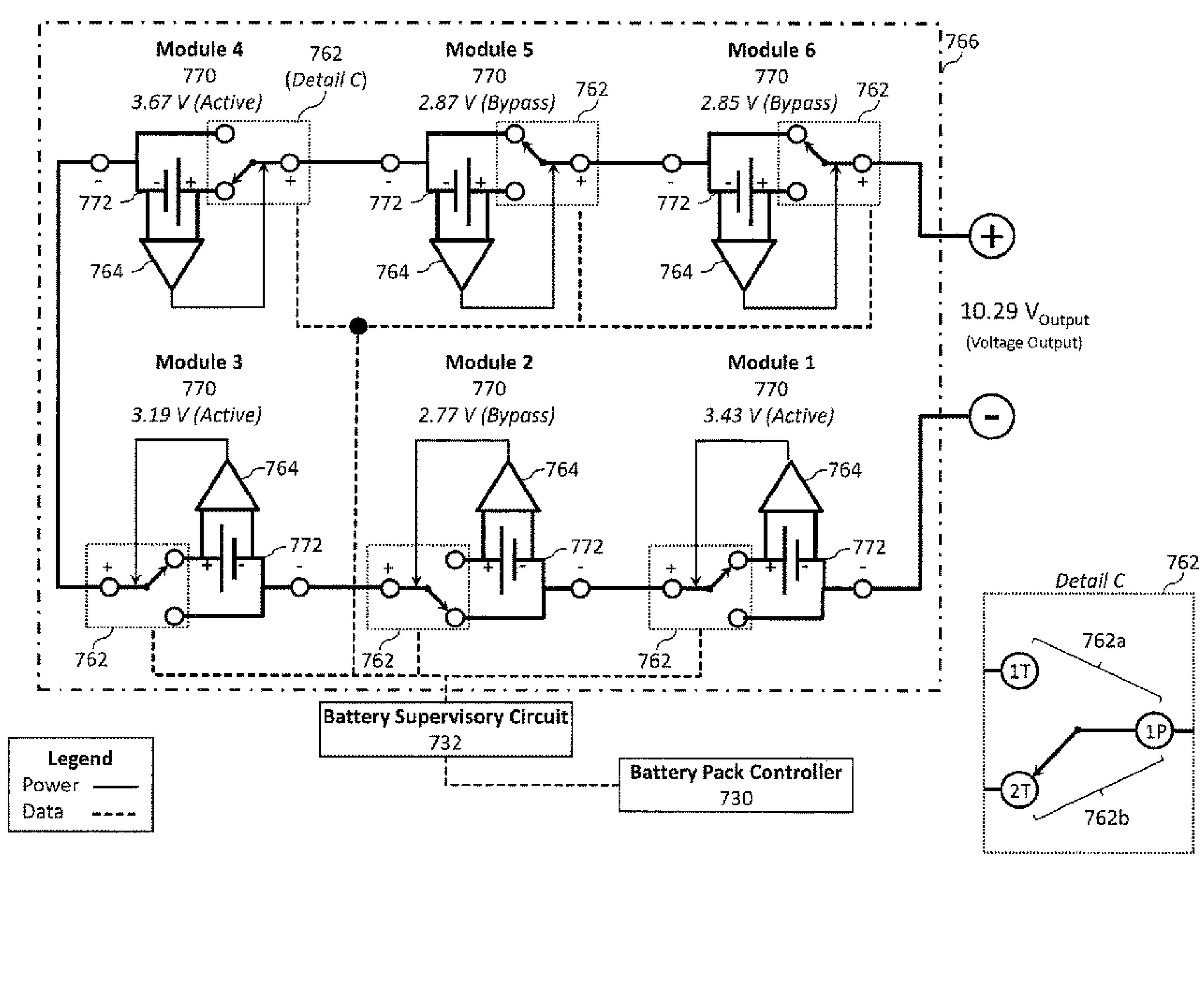
(57) **ABSTRACT**

The present disclosure relates to a reconfigurable battery system and method of operating the same. The reconfigurable battery system comprising a plurality of switchable battery modules, a battery supervisory circuit, and a battery pack controller, where the plurality of switchable battery modules electrically arranged in series to define a battery string defining an output voltage. The battery pack controller operably coupled to the battery supervisory circuit to selectively switch, for each of the plurality of switchable battery modules, the battery switch between the first position and the second position such that the output voltage is substantially equal to a predetermined target output voltage.

20 Claims, 11 Drawing Sheets



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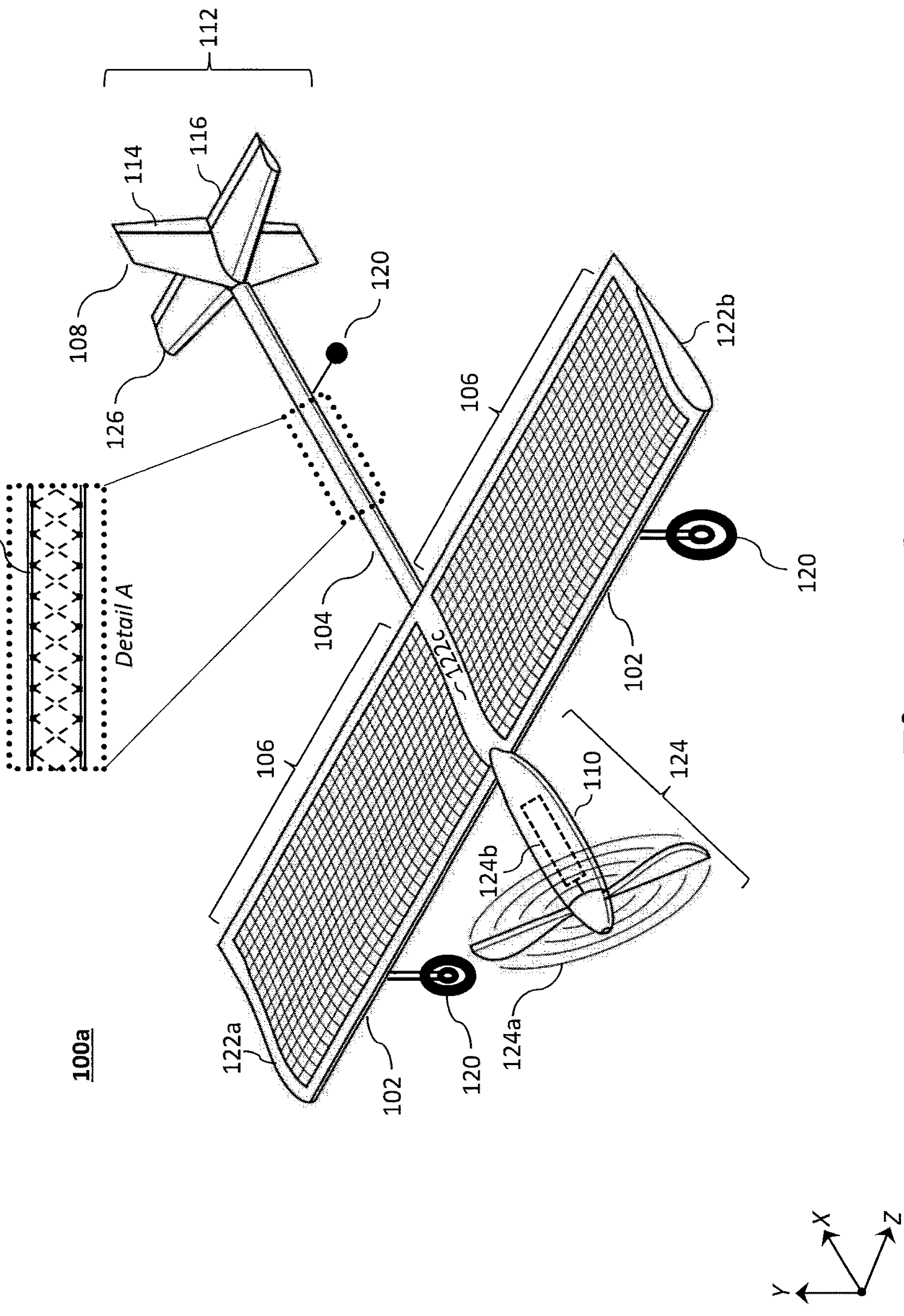

100a
112
116
114
108
126
120
118
Detail A
104
106
122b
120
102
122c
106
110
124
124b
122a
102
120
124a
X
Y
Z

Figure 1a

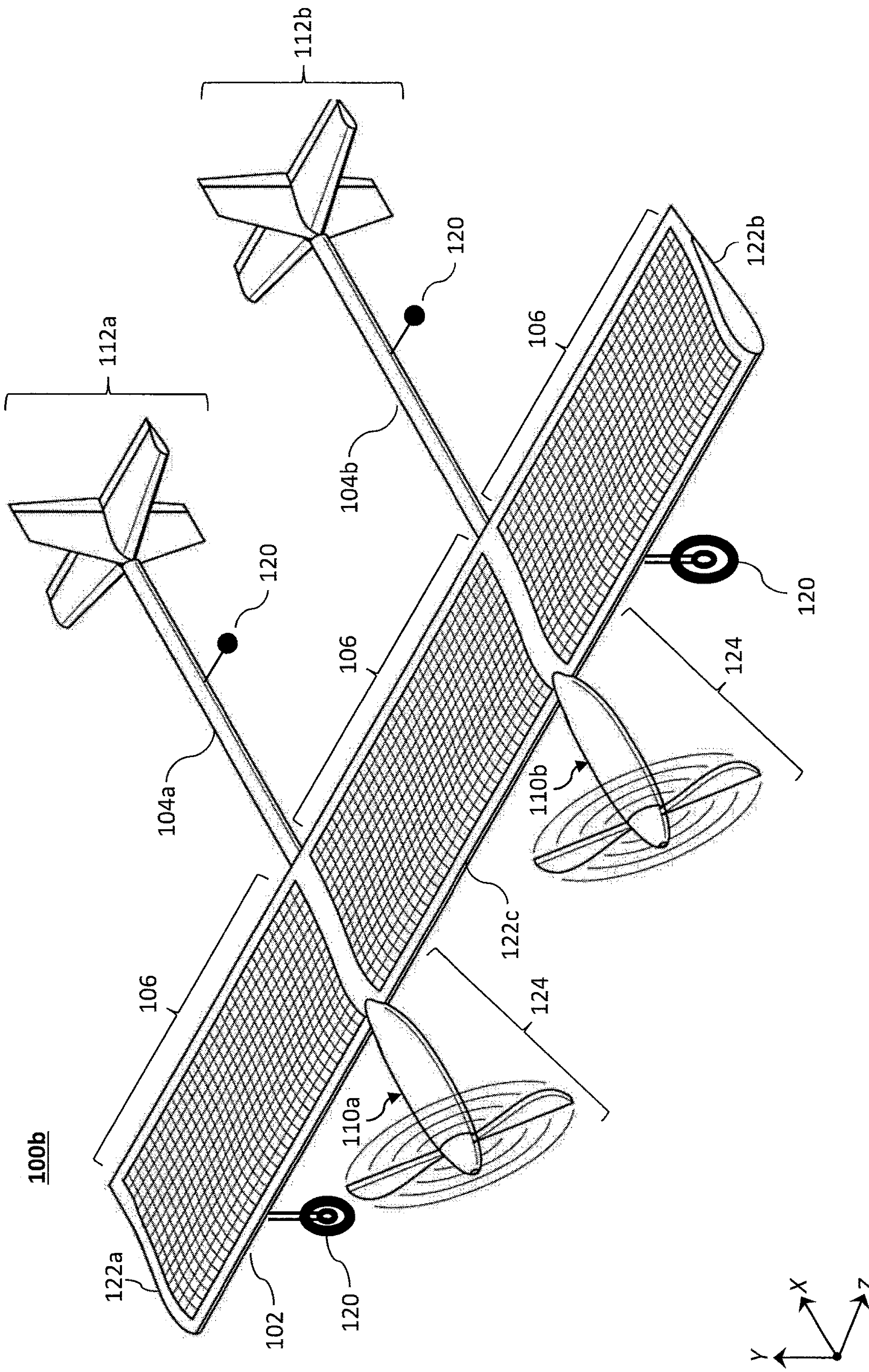

100b
102
104a
104b
106
106
106
110a
110b
112a
112b
120
120
120
120
122a
122b
122c
124
124
X
Y
Z

Figure 1b

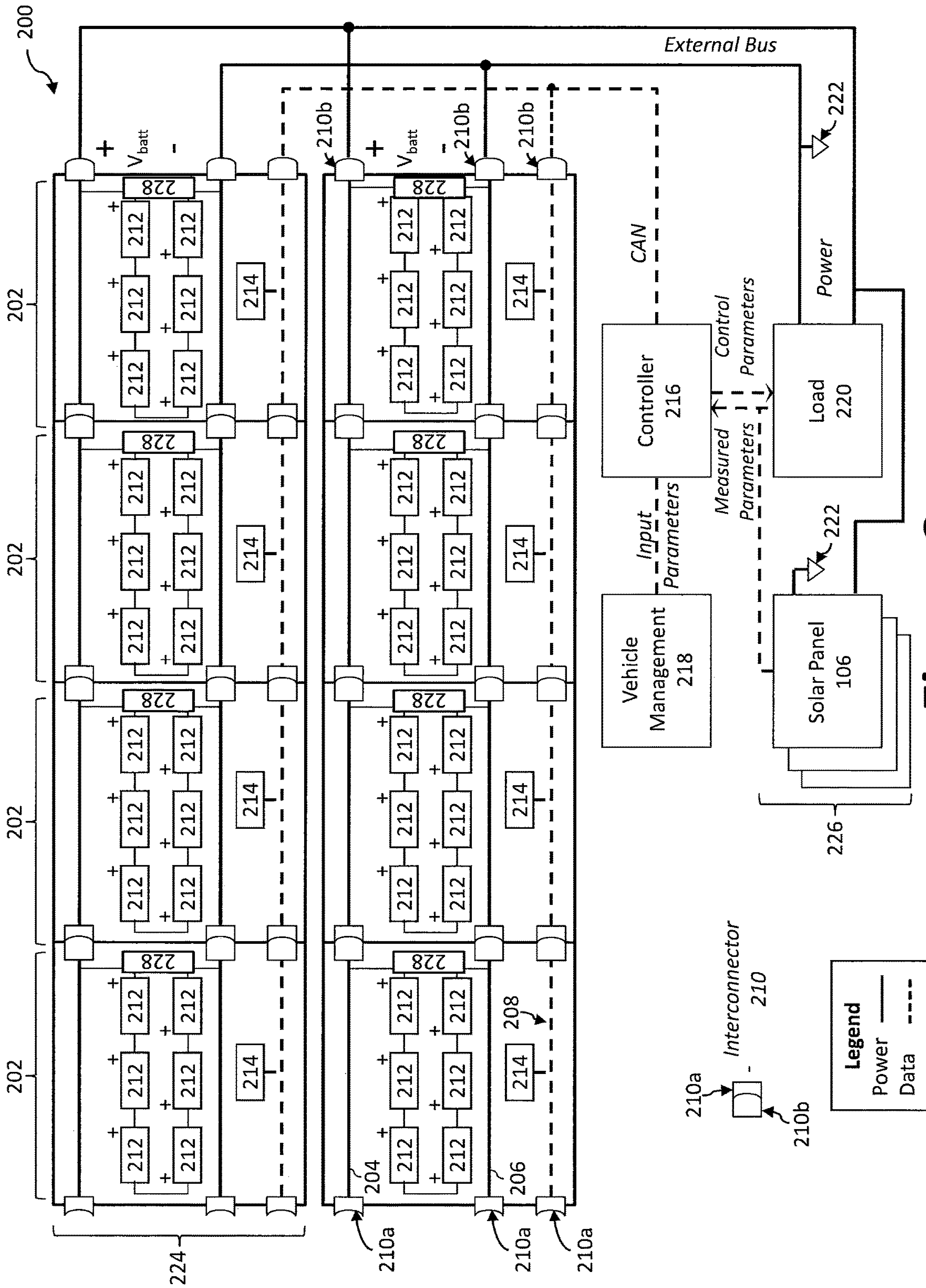

200
External Bus
CAN
Power
222
202
224
228
212
214
204
206
208
210a
210b
+ V_{batt} -
Controller 216
Control Parameters
Measured Parameters
Input Parameters
Load 220
Vehicle Management 218
Solar Panel 106
226
Interconnector 210
Legend
Power
Data

Figure 2

300

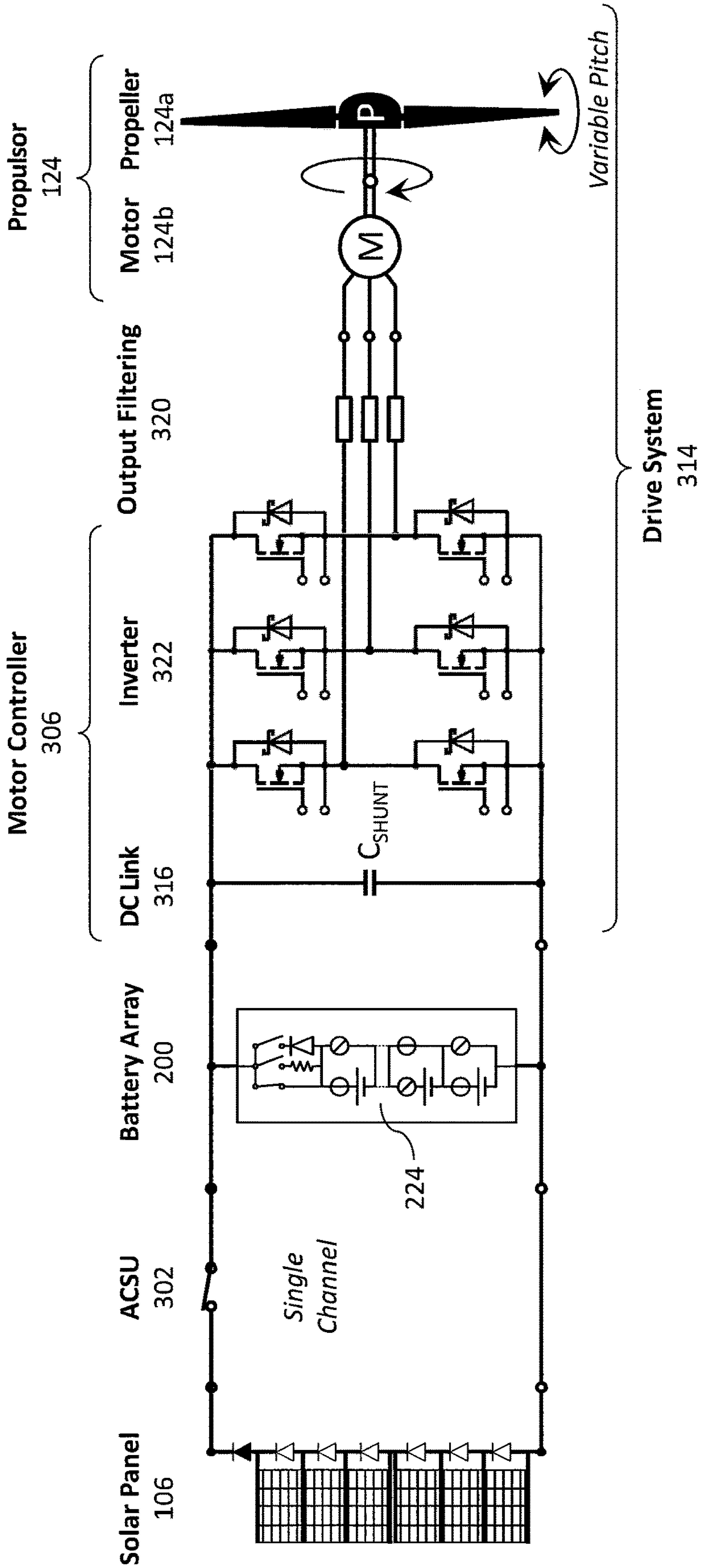

Propulsor
124
Motor
124b
Propeller
124a
P
M
Variable Pitch
Motor Controller
306
DC Link
316
Inverter
322
Output Filtering
320
Drive System
314
C_{SHUNT}
Battery Array
200
224
ACSU
302
Single
Channel
Solar Panel
106

Figure 3

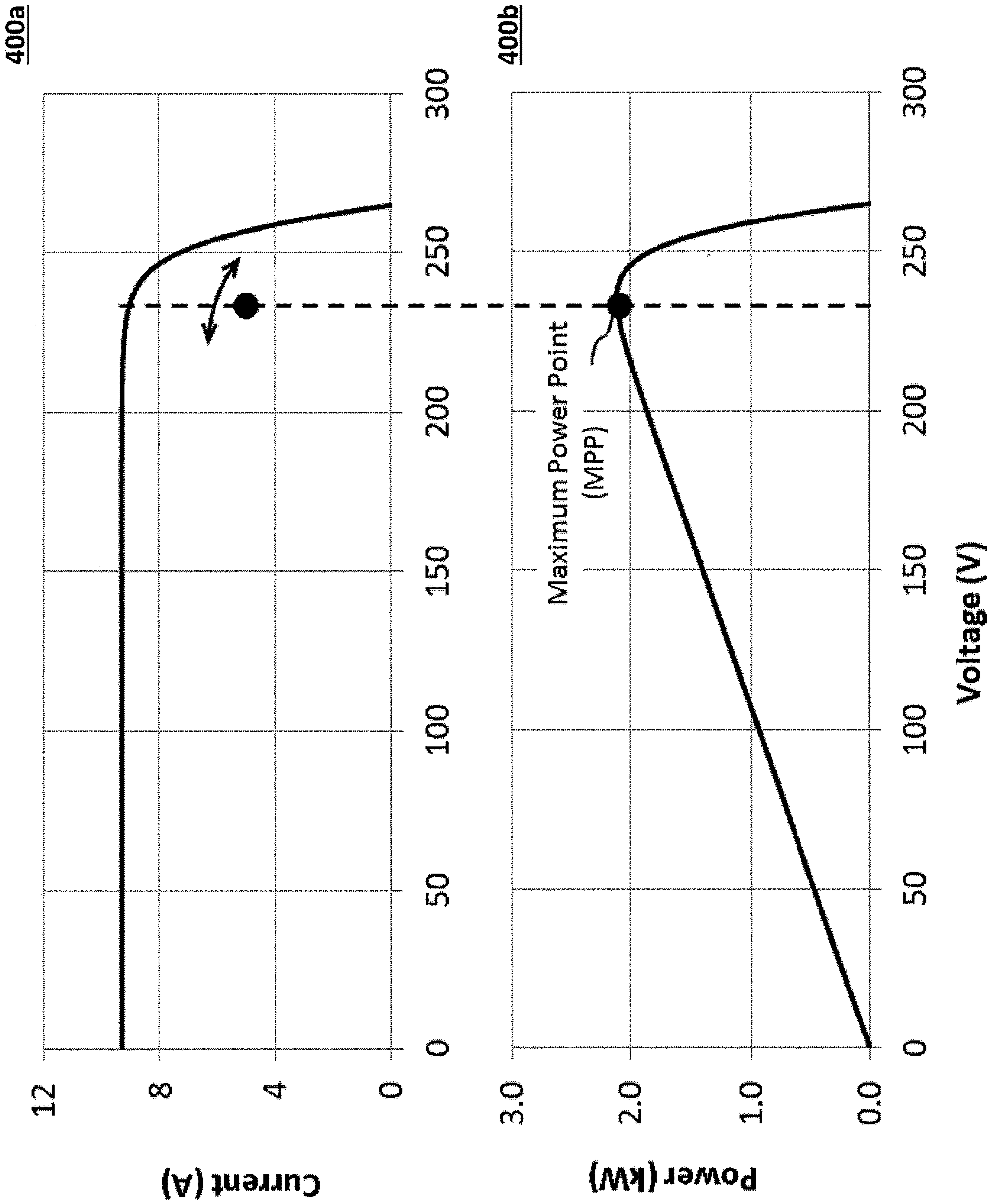

400a
400b
Current (A)
Power (kW)
Voltage (V)
Maximum Power Point (MPP)
0
4
8
12
0.0
1.0
2.0
3.0
0
50
100
150
200
250
300

Figure 4

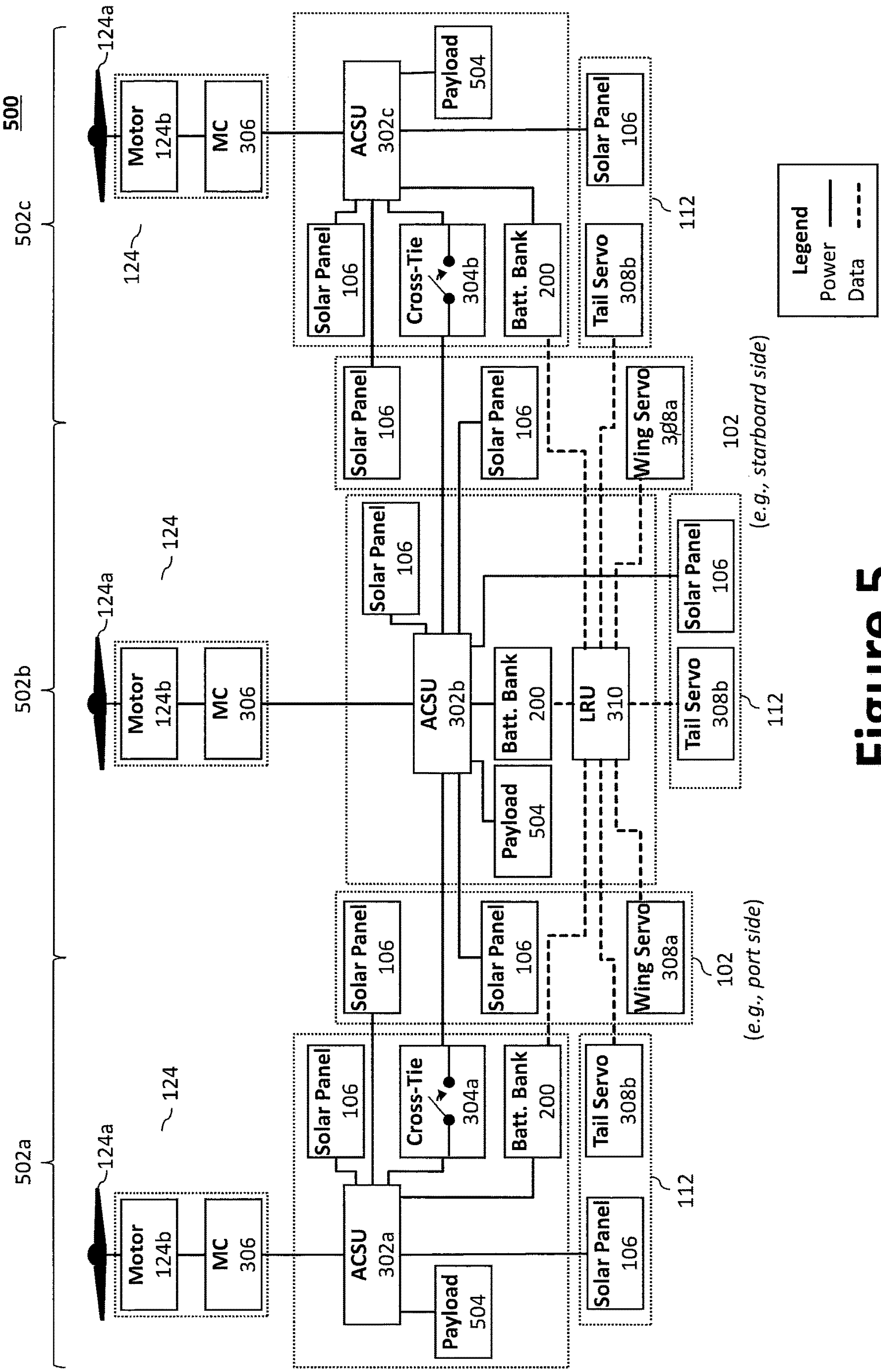

500
502a
502b
502c
124
124a
Motor 124b
MC 306
ACSU 302a
ACSU 302b
ACSU 302c
Payload 504
Solar Panel 106
Cross-Tie 304a
Cross-Tie 304b
Batt. Bank 200
Tail Servo 308b
Wing Servo 308a
LRU 310
112
102 (e.g., port side)
102 (e.g., starboard side)
Legend
Power
Data

Figure 5

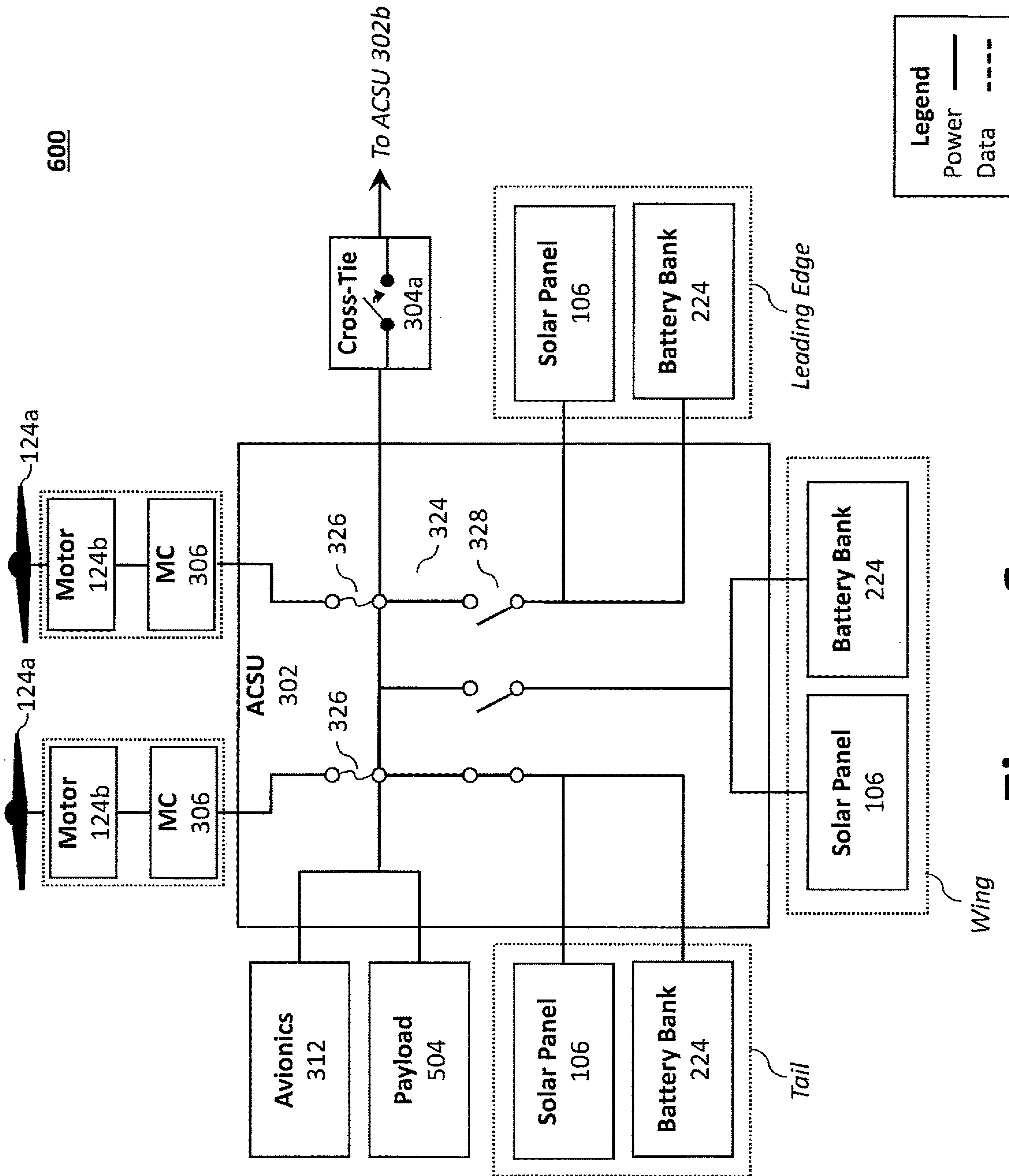
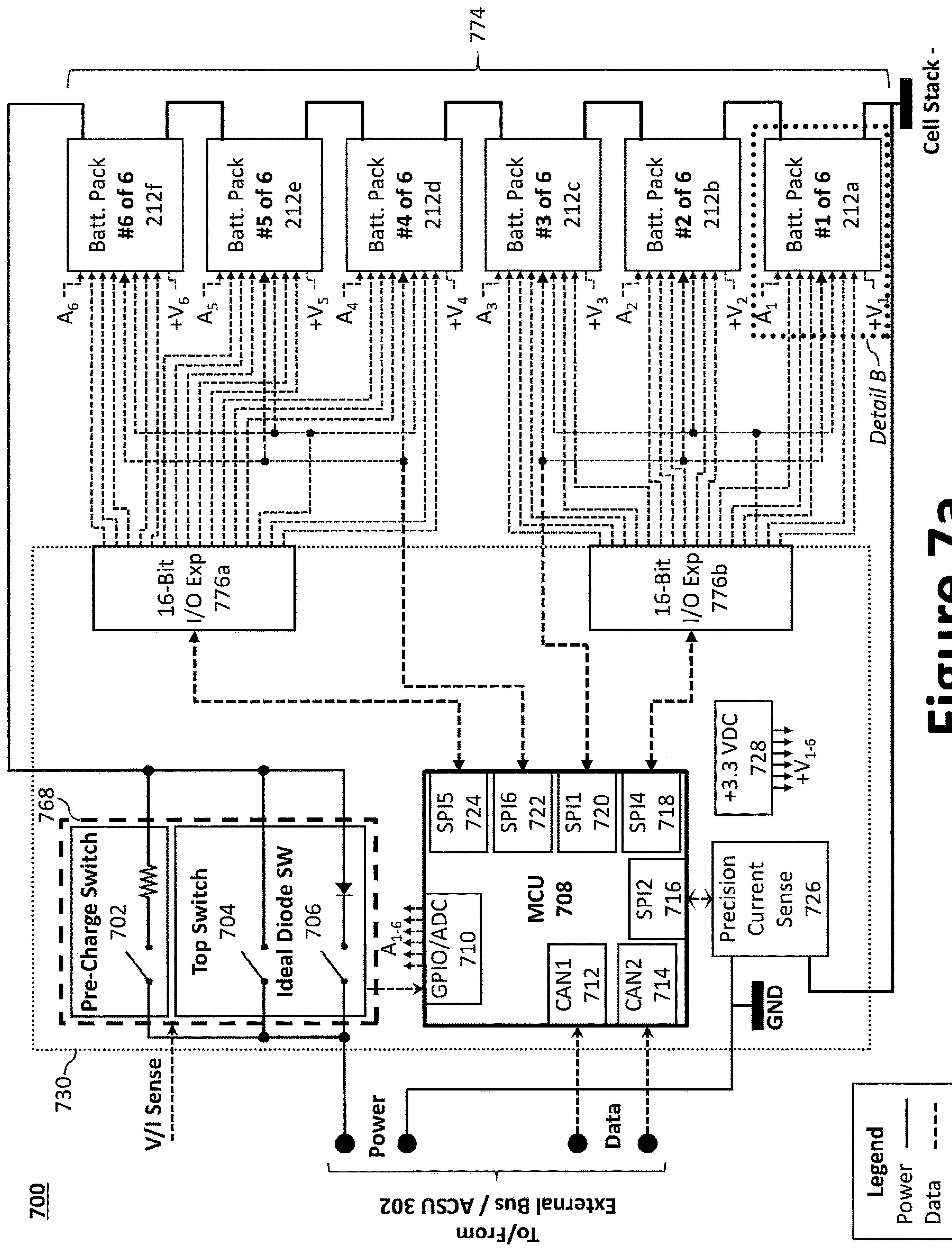

600
To ACSU 302b
Cross-Tie
304a
124a
124a
Motor
124b
MC
306
Motor
124b
MC
306
ACSU
302
326
326
324
328
Solar Panel
106
Battery Bank
224
Leading Edge
Battery Bank
224
Solar Panel
106
Wing
Avionics
312
Payload
504
Solar Panel
106
Battery Bank
224
Tail
Legend
Power
Data

Figure 6



700
730
768
774
V/I Sense
Power
Data
To/From
External Bus / ACSU 302
Pre-Charge Switch
702
Top Switch
704
Ideal Diode SW
706
GPIO/ADC
710
MCU
708
CAN1
712
CAN2
714
SPI2
716
SPI4
718
SPI1
720
SPI6
722
SPI5
724
Precision Current Sense
726
+3.3 VDC
728
$+V_{1-6}$
A_{1-6}
GND
16-Bit I/O Exp
776a
16-Bit I/O Exp
776b
Batt. Pack
#6 of 6
212f
Batt. Pack
#5 of 6
212e
Batt. Pack
#4 of 6
212d
Batt. Pack
#3 of 6
212c
Batt. Pack
#2 of 6
212b
Batt. Pack
#1 of 6
212a
A_6
$+V_6$
A_5
$+V_5$
A_4
$+V_4$
A_3
$+V_3$
A_2
$+V_2$
A_1
$+V_1$
Detail B
Cell Stack -
Legend
Power
Data

Figure 7a

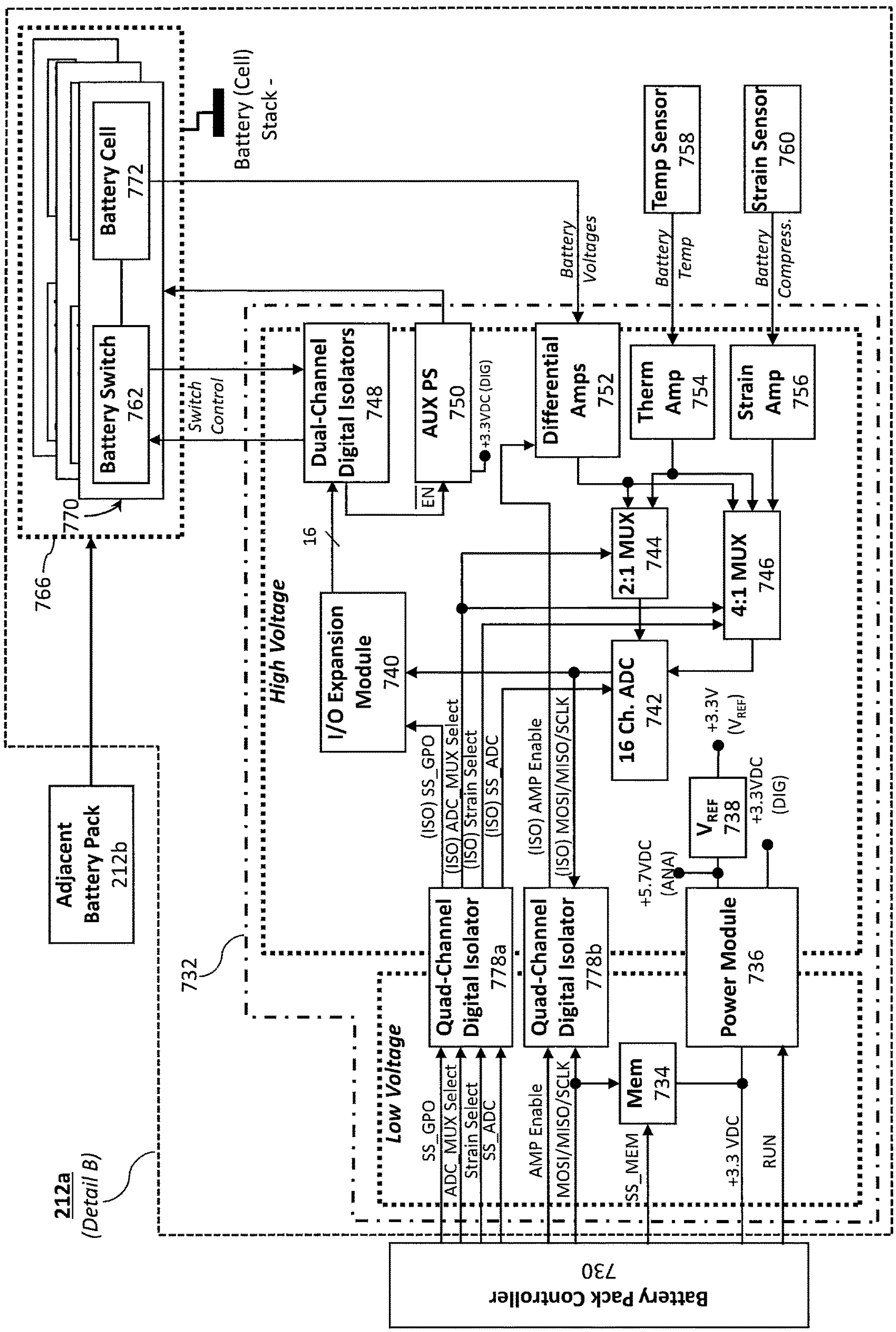

Battery Cell 772
Battery Switch 762
770
766
Battery (Cell) Stack -
Switch Control
Battery Voltages
Temp Sensor 758
Strain Sensor 760
Battery Temp
Battery Compress.
Dual-Channel Digital Isolators 748
AUX PS 750
EN
+3.3VDC (DIG)
Differential Amps 752
Therm Amp 754
Strain Amp 756
2:1 MUX 744
4:1 MUX 746
16
High Voltage
I/O Expansion Module 740
16 Ch. ADC 742
+3.3V (V_{REF})
V_{REF} 738
+3.3VDC (DIG)
+5.7VDC (ANA)
(ISO) SS_GPO
(ISO) ADC_MUX Select
(ISO) Strain Select
(ISO) SS_ADC
(ISO) AMP Enable
(ISO) MOSI/MISO/SCLK
Adjacent Battery Pack 212b
732
Quad-Channel Digital Isolator 778a
Quad-Channel Digital Isolator 778b
Power Module 736
Low Voltage
Mem 734
SS_GPO
ADC_MUX Select
Strain Select
SS_ADC
AMP Enable
MOSI/MISO/SCLK
SS_MEM
+3.3 VDC
RUN
212a (Detail B)
Battery Pack Controller 730

Figure 7b

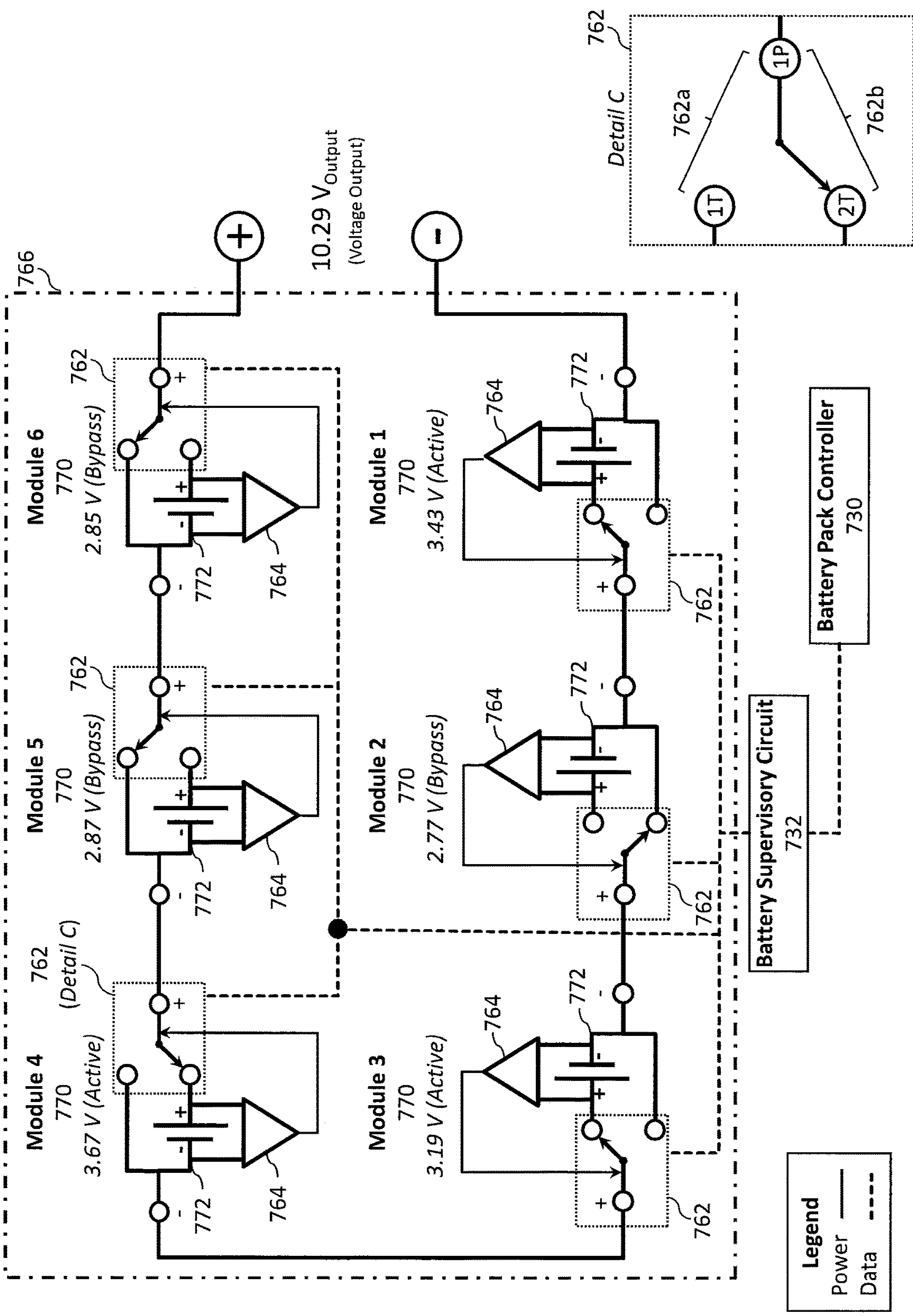

766
10.29 V_{Output}
(Voltage Output)
Module 6
770
2.85 V (Bypass)
Module 5
770
2.87 V (Bypass)
Module 4
770
3.67 V (Active)
Module 1
770
3.43 V (Active)
Module 2
770
2.77 V (Bypass)
Module 3
770
3.19 V (Active)
762
762 (Detail C)
764
772
Battery Pack Controller
730
Battery Supervisory Circuit
732
Legend
Power
Data
Detail C
762a
762b
1P
1T
2T

Figure 7c

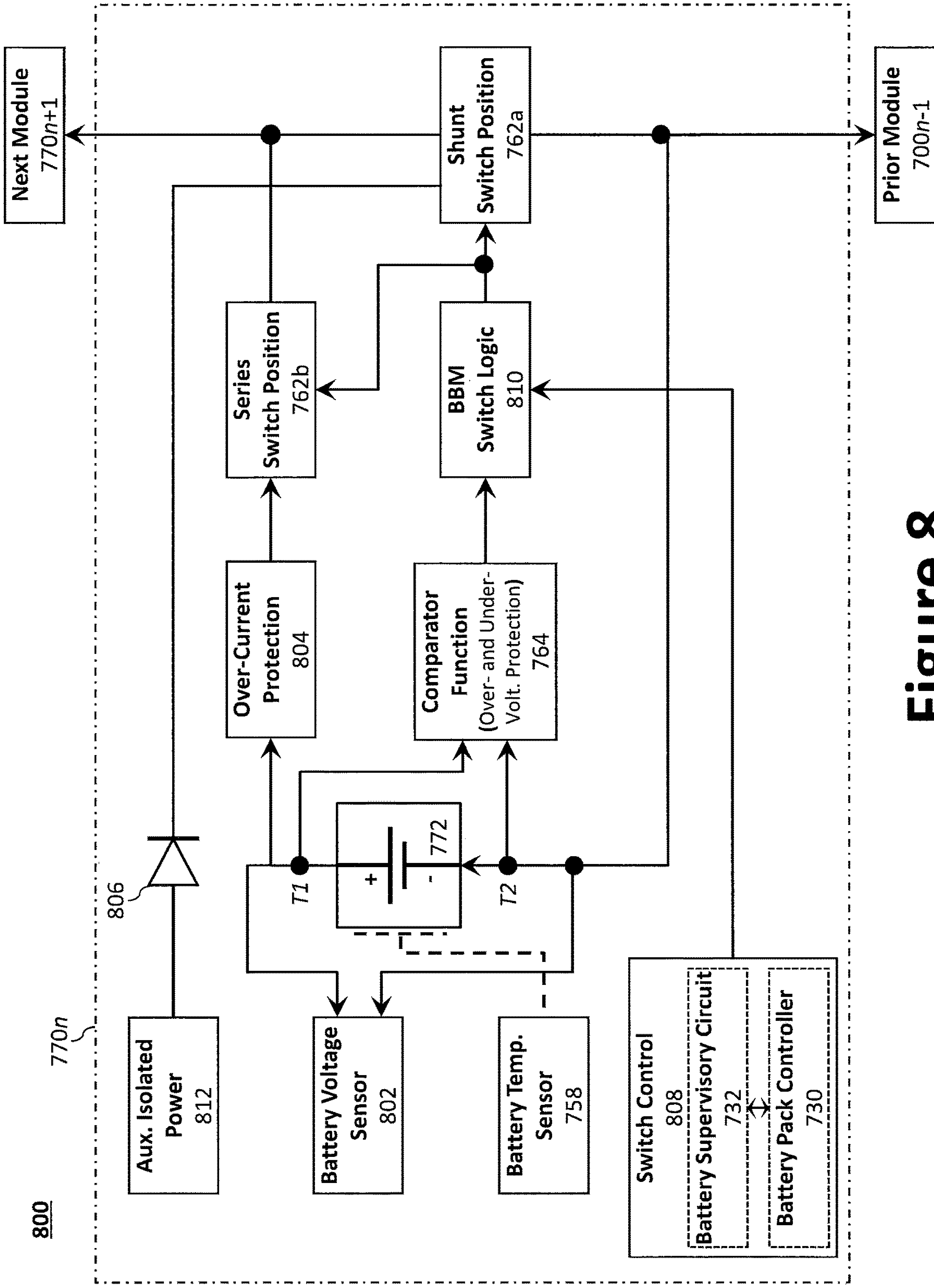

800
770n
Next Module
770n+1
Prior Module
700n-1
Shunt
Switch Position
762a
Series
Switch Position
762b
BBM
Switch Logic
810
Over-Current
Protection
804
Comparator
Function
(Over- and Under-
Volt. Protection)
764
806
T1
T2
+
-
772
Aux. Isolated
Power
812
Battery Voltage
Sensor
802
Battery Temp.
Sensor
758
Switch Control
808
Battery Supervisory Circuit
732
Battery Pack Controller
730

Figure 8

PROGRAMMABLE BATTERY PACK

FIELD

The present disclosure relates to battery power systems and methods, such as those suitable for use with aircraft.

BACKGROUND

The concept of high-altitude, long-endurance, solar-powered aircraft has been demonstrated by a number of aerial vehicle research projects. Solar power systems typically rely on an array of solar panels that interface with a battery grid (or similar battery systems) through control circuitry, such as a maximum power point (MPP) tracker.

An MPP tracker provides a circuit assembly that, in operation, adjusts the load impedance presented to the array of solar panels to achieve a maximum power out of the solar array. The power collected out of the solar array is then stored to the battery packs/assemblies of the battery grid. A maximum power point (MPP) tracker and other battery power systems, however, introduce additional weight and complexity to the overall system.

A need exists for solar and battery power systems and methods that can overcome the deficiencies of the prior art. Such a lightweight, efficient battery packs and battery pack assemblies may be employed with ultralight aircraft applications, such as long endurance solar-powered aircraft.

SUMMARY

The present disclosure relates to battery power systems and methods, such as those suitable for use with aircraft.

According to a first aspect, a method is provided for reconfiguring a battery system having a battery pack controller operably coupled to a plurality of switchable battery modules that are electrically arranged in series to define a battery string defining an output voltage, each of the plurality of switchable battery modules comprising a battery and a battery switch associated therewith, each battery switch configured to selectively connect its battery to the battery string when in a first position and to bypass its battery when in a second position, the method comprising: monitoring, for each of the plurality of switchable battery modules, one or more parameters of the battery via a battery supervisory circuit; and selectively switching, for each of the plurality of switchable battery modules, the battery switch between a first position and a second position via the battery pack controller as a function of the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage.

In certain aspects, the one or more parameters include a voltage for the battery of each of the plurality of switchable battery modules.

In certain aspects, the battery pack controller is configured to control the plurality of switchable battery modules based at least in part on instructions received from a solar array consolidation and switching unit (ACSU).

In certain aspects, the method further comprises the step of maintaining the battery switch in the second position via an auxiliary isolated power source when an open battery terminal condition occurs.

In certain aspects, the method further comprises the step of preventing back-feeding of current into the auxiliary isolated power source via a blocking diode.

In certain aspects, the method further comprises the step of using a comparator to provide, for each of the plurality of switchable battery modules, voltage protection to the battery.

In certain aspects, the method further comprises the step of using the comparator to provide, for each of the plurality of switchable battery modules, both over-voltage protection and under-voltage protection to the battery.

In certain aspects, the method further comprises the step of overriding a battery switch signal from the battery pack controller in an under-voltage condition.

According to a second aspect, a reconfigurable battery system comprises: a plurality of switchable battery modules electrically arranged in series to define a battery string defining an output voltage, each of the plurality of switchable battery modules comprising a battery and a battery switch, wherein configuring the battery switch in a first position electrically places the battery in series with the battery string to increase the output voltage, and wherein configuring the battery switch in a second position electrically bypasses the battery from the battery string; a battery supervisory circuit operably coupled to each of the plurality of switchable battery modules, wherein the battery supervisory circuit is configured to monitor, for each of the plurality of switchable battery modules, one or more parameters of the battery; and a battery pack controller operably coupled to the battery supervisory circuit to selectively switch, for each of the plurality of switchable battery modules, the battery switch between the first position and the second position based at least in part on the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage.

In certain aspects, the one or more parameters include a voltage for each battery.

In certain aspects, the one or more parameters further includes a measured current passing through the battery string.

In certain aspects, the plurality of switchable battery modules are arranged into a battery pack that is electrically arranged in series with a second battery pack to define a battery pack assembly.

In certain aspects, the battery pack assembly is operably coupled to a second battery pack assembly in a parallel electrical arrangement to define a battery bank.

In certain aspects, the battery pack controller is configured to control the plurality of switchable battery modules based at least in part on instructions received from a solar array consolidation and switching unit (ACSU).

In certain aspects, each of the plurality of switchable battery modules further comprises an auxiliary isolated power source to maintain the battery switch in the second position when an open battery terminal condition occurs.

In certain aspects, the auxiliary isolated power source is operatively coupled to the battery switch via a blocking diode to prevent back-feeding into the auxiliary isolated power source.

In certain aspects, the reconfigurable battery system further comprises, for each of the plurality of switchable battery modules, a comparator to provide voltage protection to the battery.

In certain aspects, the comparator is configured to provide, for each of the plurality of switchable battery modules, both over-voltage and under-voltage protection to the battery.

In certain aspects, the reconfigurable battery system is configured to override a battery switch signal from the battery pack controller in an under-voltage condition.

In certain aspects, for each of the plurality of switchable battery modules, an isolator is positioned between the between the battery switch and the battery pack controller.

DRAWINGS

The foregoing and other objects, features, and advantages of the devices, systems, and methods described herein will be apparent from the following description of particular embodiments thereof, as illustrated in the accompanying figures; where like reference numbers refer to like structures. The figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the devices, systems, and methods described herein.

FIG. **1***a* illustrates an example solar-powered aircraft in accordance with a first aspect.

FIG. **1***b* illustrates an example solar-powered aircraft in accordance with a second aspect.

FIG. **2** illustrates an example solar power system having a battery array.

FIG. **3** illustrates an example simplified single power channel for a solar-powered aircraft.

FIG. **4** illustrates a set of charts illustrating a maximum power point.

FIG. **5** illustrates an example electrical power system for the solar-powered aircraft.

FIG. **6** illustrates an example power diagram for an array consolidation and switching unit (ACSU).

FIG. **7***a* illustrates a block diagram of a battery management system.

FIG. **7***b* illustrates a block diagram of an example battery pack of a battery management system.

FIG. **7***c* illustrates a diagram of an example battery string of a battery pack.

FIG. **8** illustrates an example architecture for a switchable battery module.

DESCRIPTION

References to items in the singular should be understood to include items in the plural, and vice versa, unless explicitly stated otherwise or clear from the text. Grammatical conjunctions are intended to express any and all disjunctive and conjunctive combinations of conjoined clauses, sentences, words, and the like, unless otherwise stated or clear from the context. Recitation of ranges of values herein are not intended to be limiting, referring instead individually to any and all values falling within the range, unless otherwise indicated herein, and each separate value within such a range is incorporated into the specification as if it were individually recited herein. In the following description, it is understood that terms such as "first," "second," "top," "bottom," "side," "front," "back," and the like are words of convenience and are not to be construed as limiting terms.

As used herein, the terms "about," "approximately," "substantially," or the like, when accompanying a numerical value, are to be construed as indicating a deviation as would be appreciated by one of ordinary skill in the art to operate satisfactorily for an intended purpose. Ranges of values and/or numeric values are provided herein as examples only, and do not constitute a limitation on the scope of the described embodiments. The use of any and all examples, or exemplary language ("e.g.," "such as," or the like) provided herein, is intended merely to better illuminate the embodiments and does not pose a limitation on the scope of the embodiments. The terms "e.g.," and "for example" set off lists of one or more non-limiting examples, instances, or illustrations. No language in the specification should be construed as indicating any unclaimed element as essential to the practice of the embodiments.

As used herein, the terms "circuits" and "circuitry" refer to physical electronic components (i.e., hardware) and any software and/or firmware ("code"), which may configure the hardware, be executed by the hardware, and or otherwise be associated with the hardware. As used herein, for example, a particular processor and memory may comprise a first "circuit" when executing a first one or more lines of code and may comprise a second "circuit" when executing a second one or more lines of code.

As used herein, the terms "aerial vehicle" and "aircraft" are used interchangeably and refer to a machine capable of flight, including, but not limited to, both traditional runway and vertical takeoff and landing ("VTOL") aircraft, and also including both manned and unmanned aerial vehicles ("UAV"). VTOL aircraft may include fixed-wing aircraft (e.g., Harrier jets), rotorcraft (e.g., helicopters, multirotor, etc.), and/or tilt-rotor/tilt-wing aircraft.

As used herein, the term "and/or" means any one or more of the items in the list joined by "and/or." As an example, "x and/or y" means any element of the three-element set {(x), (y), (x, y)}. In other words, "x and/or y" means "one or both of x and y". As another example, "x, y, and/or z" means any element of the seven-element set {(x), (y), (z), (x, y), (x, z), (y, z), (x, y, z)}. In other words, "x, y, and/or z" means "one or more of x, y, and z."

As used herein, the term "composite material" as used herein, refers to a material comprising an additive material and a matrix material. For example, a composite material may comprise a fibrous additive material (e.g., fiberglass, glass fiber ("GF"), carbon fiber ("CF"), aramid/para-aramid synthetic fibers, etc.) and a matrix material (e.g., epoxies, polyimides, and alumina, including, without limitation, thermoplastic, polyester resin, polycarbonate thermoplastic, casting resin, polymer resin, acrylic, chemical resin). In certain aspects, the composite material may employ a metal, such as aluminum and titanium, to produce fiber metal laminate (FML) and glass laminate aluminum reinforced epoxy (GLARE). Further, composite materials may include hybrid composite materials, which are achieved via the addition of some complementary materials (e.g., two or more fiber materials) to the basic fiber/epoxy matrix.

As used herein, the term "composite laminates" as used herein, refers to a type of composite material assembled from layers (i.e., a "ply") of additive material and a matrix material.

As used herein, the terms "communicate" and "communicating" refer to (1) transmitting, or otherwise conveying, data from a source to a destination, and/or (2) delivering data to a communications medium, system, channel, network, device, wire, cable, fiber, circuit, and/or link to be conveyed to a destination.

As used herein, the term "processor" means processing devices, apparatuses, programs, circuits, components, systems, and subsystems, whether implemented in hardware, tangibly embodied software, or both, and whether or not it is programmable. The term "processor" as used herein includes, but is not limited to, one or more computing devices, hardwired circuits, signal-modifying devices and systems, devices and machines for controlling systems, central processing units, programmable devices and systems, field-programmable gate arrays, application-specific integrated circuits, systems on a chip, systems comprising discrete elements and/or circuits, state machines, virtual machines, data processors, processing facilities, and combinations of any of the foregoing. The processor may be, for example, any type of general purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, an application-specific integrated circuit (ASIC). The processor may be coupled to, or integrated with a memory device. The memory device can be any suitable type of computer memory or any other type of electronic storage medium, such as, for example, read-only memory (ROM), random access memory (RAM), cache memory, compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically-erasable programmable read-only memory (EEPROM), a computer-readable medium, or the like.

As used herein, the term "solar panel" refers to an array of one or more photovoltaic cells configured to collect solar energy to generate electrical power. The solar panels may employ one or more of the following solar cell types: monocrystalline silicon solar cells, polycrystalline silicon solar cells, string ribbon solar cells, thin-film solar cells (TFSC), cadmium telluride (CdTe) solar cells, copper indium gallium selenide (CIS/CIGS) solar cells, and the like. To reduce overall weight and to improve reliability and durability, it is advantageous to employ light weight and/or flexible solar panels (e.g., thin-film solar panels).

As used herein, circuitry or a device is "operable" to perform a function whenever the circuitry or device comprises the necessary hardware and code (if any is necessary) to perform the function, regardless of whether performance of the function is disabled, or not enabled (e.g., by a user-configurable setting, factory trim, etc.).

FIGS. **1***a* and **1***b* illustrate example solar-powered aircraft **100***a*, **100***b*. Specifically, FIG. **1***a* illustrates an isometric view of a first solar-powered aircraft **100***a* with a single fuselage **110** and tail boom **104**, while FIG. **1***b* illustrates an isometric view of a second solar-powered aircraft **100***b* with a set of two side-by-side fuselages **110***a*, **110***b* and a set of two side-by-side first and second tail booms **104***a*, **104***b*. As illustrated, each of the two side-by-side fuselages **110***a*, **110***b* may include a propulsor **124**. The solar-powered aircraft **100***a*, **100***b* generally comprises a wing **102**, one or more propulsors **124** (e.g., a propeller **124***a* and associated gearing, which is axially driven by one or more motors **124***b*), one or more fuselages **110** (e.g., a single fuselage **110** or a set of fuselages **110***a*, **110***b*), one or more tail booms **104** (e.g., a single tail boom **104** or a set of tail booms **104***a*, **104***b*; each illustrated as an elongated boom coupled to the aft end of a fuselage **110**), one or more tail sections **112** (e.g., a single tail section **112** or a set of tail sections **112***a*, **112***b*), and landing gear **120**. As illustrated, the wing **102** comprises a first wing tip **122***a* (port side), a second wing tip **122***b* (starboard side), and a midpoint **122***c* along the wing's **102** wingspan that is approximately half way between the first wing tip **122***a* and the second wing tip **122***b*.

The various structural components of the solar-powered aircraft **100***a*, **100***b* may be fabricated from metal, a composite material, or a combination thereof. For example, portions of the wing **102** may be fabricated using fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and/or any other suitable type of additive manufacturing/3D printing. A benefit of this fabrication method is that it produces a high-performing, more stable aircraft, using advanced sensing and 3D printing disciplines. FDM is a thermal polymer layer deposition process that produces components one layer at a time, effectively printing aircraft components rapidly, in low-volume, and to exacting material specifications. Using FDM, numerous wing design iterations may be inexpensively manufactured to meet desired strength and stiffness requirements, control surface sizing, and other characteristics. Further, additional wing panels/components may be fabricated to allow for tailored sensor integration, ease of generating additional actuation schemes or altering the control surface placement, ease of characterizing the strain on the wing, and an ability to easily alter the wing's stiffness to provide the best platform for proprioceptive sensing in a given application. This capability also offers robustness against wing damage, as replacement components are readily reproducible.

Each propulsor **124** generally comprises a motor **124***b* coupled to, and configured to drive/rotate, a propeller **124***a*. The motor **124***b* may be an electric motor controlled via a motor controller **306**, such as an electronic speed controller (ESC) unit. To that end, an ESC unit (or another motor controller **306**) may be provided to control the motor **124***b*, which may be coupled (or otherwise integrated) with the wing **102** (e.g., as part of a nacelle pod). The propulsor **124** may be positioned on the wing **102**, the tail boom **104** (e.g., at the proximal end), or a combination thereof. For example, each of the propulsors **124** may be positioned on, or within, the wing **102** in either a pusher configuration or a tractor configuration (as illustrated). Further, while each fuselage **110** is illustrated as having a single propulsor **124** associated therewith, additional propulsors **124** may be provided. Regardless of the propulsion configuration, each of the plurality of propulsors **124** may be oriented to direct thrust toward the distal end of the tail boom **104** (aft).

The wing **102** and/or the horizontal stabilizer **126** may comprise one or more arrays of solar panels **106** to generate power. As illustrated in FIG. **1***a*, the solar panels **106** may be positioned on each side of the tail boom **104**/fuselage **110** along the upper surface of the wing **102**. The solar-powered aircraft **100***a*, **100***b* may further comprise one or more energy storage devices operatively coupled to the solar panels **106** to power the vehicle management system **218** and various electric loads. The one or more energy storage devices store collected solar energy for later use by the solar-powered aircraft **100***a*, **100***b* (e.g., when sunlight is unavailable, typically at nighttime). As used herein "energy storage device" refers to a battery or similar instrumentality known to those of skill in the art capable of storing and transmitting energy collected from the solar panels **106**, including but not limited to a rechargeable battery (e.g., lithium-polymer batteries), a regenerative fuel cell, or combinations thereof.

While the wing **102** is illustrated as generally linear with non-tapered outboard portions, other configurations are contemplated, such as back-swept, tapered, rectangular, elliptical, forward-swept, and the like. Therefore, the wing **102** may be any type of fixed wing, including, but not limited to, a straight wing, a swept wing, a forward-swept wing, a dihedral wing (an upward angle from horizontal), an anhedral wing (a negative dihedral angle—downward angle from horizontal), or any other suitable type of fixed wing as known by those of ordinary skill in the art. As illustrated, the wingspan of the wing **102** may be substantially perpendicular relative to the longitudinal length of the fuselage(s) **110** and tail boom(s) **104**; however, the wing **102** may instead be swept back or swept forward. In certain aspects, the wing **102** may be modular and configured for disassembly;

thereby allowing the solar-powered aircraft **100***a*, **100***b* to be more easily transported by land and/or to physically fit within a hanger or other structure for storage. For example, the wing **102** may be fabricated from a plurality of wing panel modules and removably joined to one another end-to-end via a set of joints. Each of the joints may employ one or more fasteners (e.g., bolts, clips, etc.) and electrical connectors (e.g., plugs, contacts, etc.) to facilitate both physical and electrical coupling therebetween.

As can be appreciated, control surfaces on the wing typically require additional structural reinforcements and actuators, which result in additional weight. In addition, adding control surfaces to a wing increases the drag during flight. Further, control surfaces on a wing can also require that the skin panel be broken into sections, as opposed to having a substantially unbroken construction that allows for the solar panels **106** to cover more of the upper surface of the wing **102**. Finally, manufacturing control surfaces adds complexity as attachment mechanisms, hinges, additional parts, and/or multiple skin panels must be made. Removing the control surfaces, however, eliminates these complexities. Therefore, unlike traditional aircraft, the wing **102** need not include movable control surfaces (e.g., flaps, slats, etc.) along the trailing or leading edges of its wingspan. Indeed, to reduce weight and complexity, the wing **102** may be generally devoid of movable control surfaces. For example, the upper and lower surface of the wing **102** may be fabricated as a single piece structure without any moving parts. Control of the wing **102** may instead be achieved through control surfaces positioned on one or more of the tail sections **112** positioned at the distal end of each tail boom **104**.

The solar-powered aircraft **100***a*, **100***b* may employ one or more tail booms **104**. In one aspect, a single tail boom **104** (see FIG. **1***a*) or in other aspects, multiple tail booms, for example, a first tail boom **104***a* and a second tail boom **104***b* (see FIG. **1***b*). Regardless of configuration, each tail boom **104** defines a proximal end and a distal end, where each of the tail booms **104** may be secured at its proximal end to a fuselage **110** or a wing **102**, while being coupled to a tail section **112** at its distal end. The solar-powered aircraft **100***a*, **100***b* (e.g., the tail booms **104**, fuselages **110**, etc.) may be fabricated using a tubular core structure **118**, which may then be covered with aircraft skin (e.g., composite materials, fabric, metal, metals alloys, etc.). Detail A of FIG. **1***a* best illustrates the tubular core structure **118**, where the aircraft skin has been removed for clarity. In certain aspects, the tail boom **104** and the fuselage **110** may be fabricated as a single, unitary component. While the solar-powered aircraft **100***b* is illustrated as having two fuselages **110** and two tail booms **104**, a person of skill in the art would understand that additional, or fewer, fuselages **110**/tail booms **104** may be employed to achieve a desired function and as a function of, for example, the length of the wing **102**.

To facilitate takeoff and landing, the solar-powered aircraft **100***a*, **100***b* may be provided with one or more sets of landing gear **120**, which may be positioned on the undercarriage of the aerial vehicle. For example, a set of landing gear **120** may be provided at the underside of the wing **102**, fuselage **110**, and/or tail boom **104**. The landing gear **120** may employ, inter alia, a set of wheels (as illustrated) and/or skids. In operation, the landing gear **120** serves to support the solar-powered aircraft **100***a*, **100***b* when it is not flying; thereby allowing it to take off, land, and taxi without causing damage to the airframe.

As illustrated, each tail section **112** may comprise one or more one control surfaces to move/steer the tail section **112** in a desired direction. For example, each tail section **112** may comprise a vertical stabilizer **108** (e.g., a dorsal fin) extending vertically (above and/or below) from the tail boom **104**, a rudder **114** operatively coupled to the vertical stabilizer **108**, a horizontal stabilizer **126** extending laterally from either side of the tail boom **104**, and an elevator **116** (or portion thereof) operatively coupled to each side of the horizontal stabilizer **126**. The tail sections **112** of the solar-powered aircraft **100***a*, **100***b* may be selectively controlled (e.g., via a flight controller/vehicle management system **218**) to control the overall pitch, roll, and yaw of the solar-powered aircraft **100***a*, **100***b*, thereby obviating the need for movable control surface on the wing **102**. The elevators **116** may be used to change the pitch of the tail section **112**, while the rudder **114** may be used to change the yaw of the tail section **112**. The pitch and/or yaw of the tail sections **112** may be separately controlled via the rudders **114** and/or elevators **116** to create a local force moment at the location the tail boom **104** attaches to the wing **102**.

Each rudder **114** may be rotatably and/or hingedly coupled to a vertical stabilizer **108** via one or more hinges to enable the rudder **114** to move about an axis defined by the vertical stabilizer **108** at its trailing edge. Similarly, the elevators **116** may be rotatably and/or hingedly coupled to the horizontal stabilizer **126** via one or more hinges to enable movement about an axis defined by the horizontal stabilizer **126** at its trailing edge. In certain aspects, one or more of the rudders **114** and/or the elevators **116** may additionally be configured with a mechanism (e.g., rails, tracks, etc.) to allow for other, non-rotatable movement, such as, for example, sliding and/or lateral movement relative to the vertical or horizontal stabilizer. In alternative embodiments, one or more of the rudders **114** and/or the elevators **116** may be omitted entirely from a given tail section **112**. Depending on the desired tail configuration, the horizontal stabilizer **126** and vertical stabilizers **108** may be operatively coupled to one another as well as the tail booms **104**, or operatively coupled only to the tail booms **104**. The tail section **112** may be configured in one of multiple tail configurations, including, for example, fuselage mounted, a cruciform, T-tail, a flying tailplane, a pi-tail (i.e., π-tail), a V configuration, an inverted V configuration (i.e., "$\wedge$" configuration), a twin tail (H-tail arrangement or U-tail arrangement), etc. Further, the horizontal stabilizer **126** may be straight, back-swept, tapered, rectangular, elliptical, forward-swept, etc. In certain aspects, the tail section **112** may employ a combination H- and $\wedge$-tail arrangement where the tail section **112** comprises $\wedge$-tail surfaces that couple to the horizontal stabilizer **126** to provide a combination H- and $\wedge$-tail arrangement.

Persons of ordinary skill in the art will recognize that alternative and/or additional structural arrangements may be implemented to accommodate the design and/or operational requirements of the tail section **112**. For example, the tail section **112** may instead employ only one or more vertical stabilizer **108**, one or more horizontal stabilizer **126**, and/or slanted or offset stabilizers that have both horizontal and vertical dimensions. Additionally, or alternatively, the tail section **112** may include multiple rudders **114** on the vertical stabilizer **108** and/or a plurality of elevators **116** on each side of the horizontal stabilizer **126**.

The solar-powered aircraft **100***a*, **100***b* may employ a vehicle management system **218** operable to control the various functions of the solar-powered aircraft **100***a*, **100***b*. As illustrated in FIG. **2**, the solar-powered aircraft **100***a*, **100***b* may be equipped with one or more battery arrays **200** to supply power to the various electric loads **220**. The electric load **220** may include, for example, one or more payloads (e.g., an intelligence surveillance reconnaissance (ISR) payload), one or more motors (e.g., the motors **124***b* used in connection with the propulsors **124**), actuators (e.g., to control the flight control surfaces of the tail section **112**, landing gear **120**, and the like), etc. Each battery array **200** generally comprises one or more battery banks **224**, each battery bank **224** having a plurality of battery pack assemblies **202** electrically coupled to each other; thereby defining, along its longitudinal length, a power supply line **204**, a ground line **206**, and, where desirable, a data communication line **208**. The ground line **206** may be electrically coupled to an equipotential point **222** (e.g., ground). As illustrated, the battery pack assemblies **202** within a battery bank **224** may be arranged electrically in parallel. The data communication line **208** may be shielded so as to mitigate electromagnetic interference (EMI) for, inter alia, the power supply line **204**. The data communication line **208** may be coupled to one or more sensors or devices **214** that monitor or control, for example, the health and/or operating parameters (e.g., temperature, humidity, voltage, etc.) of each battery pack assembly **202** or battery pack **212**.

The battery pack assemblies **202** within a battery bank **224** may be electrically connected to one another via one or more interconnectors **210** to facilitate the passing of power and/or data signals from one battery pack assembly **202** to another battery pack assembly **202** (e.g., an adjacent battery pack assembly **202**). The interconnectors **210** may employ, for example, a first connector **210***a* (e.g., a female connector) and a second connector **210***b* (e.g., a male connector) configured to mate with one another. For example, when arranged in a row/string, power and/or data signals may be conveyed, or otherwise communicated, from one end (e.g., proximal end) of a battery array **200** to an opposite end (e.g., distal end) of the battery array **200** via the interconnectors **210**; each of which can provide pass through functionality in the event of an isolated battery pack assembly **202** failure. For instance, the battery pack assemblies **202** can integrate the power rails (e.g., power supply line **204**, ground line **206**) and data communication lines **208** with in-line connections such that battery pack assemblies **202** can be attached to one another to form continuous power and data pathways for feeding the load and interacting with the system controller **216**. Each of the battery pack assemblies **202** may be selectively switched online (connected) to or switched offline (disconnected) from the battery bank **224** via one or more switching units **228** (e.g., relays, solid-state switches, etc.). For example, in the event of failure/malfunction or to achieve a desired power/capacity.

In certain aspects, a battery bank **224** within the battery array **200** can be expanded and contracted as needed (e.g., additional battery pack assemblies **202** may be connected or disconnected). In other words, power and/or data signals are carried across the battery bank **224**, thereby only requiring an electrical connection at one end of the battery bank **224**. Consequently, an energy storage system having such battery banks **224** provide for quick electrical and mechanical integration. Further, the battery pack assemblies **202** may be fabricated in bulk, thereby obviating the need for costly, complicated, and potentially unreliable harnesses. In operation, the system controller **216**, which may be processor-controlled, monitors each of the one or more battery arrays **200** (and separately, each battery bank **224**, battery pack assembly **202**, or battery cells **772**), the one or more solar panels **106** (e.g., a solar array **226** composed of at least two solar panels **106**), and the one or more electric loads **220**. For instance, in response to an input parameter (e.g., an instruction from the solar-powered aircraft's **100** vehicle management system **218**), the system controller **216** may adjust the electric load **220** and/or adjust (or reallocate) power from the one or more battery arrays **200** to meet the electric load's **220** needs. To that end, the system controller **216** may incorporate, or be operatively coupled with, a plurality of battery pack controllers. The system controller **216** may communicate through either a simplex or redundant communications bus to each of the battery pack assemblies **202** in an energy storage system (e.g., battery array **200** or battery bank **224**). The system controller **216** may employ one or more control area network (CAN) buses for monitoring, communication, and/or control, while an external bus may be used to transfer power between the battery bank(s) **224** (or components thereof) and the electric load **220** or solar array **226**. In certain aspects, as will be discussed below, the battery array **200** may employ a power allocation switching unit system and/or algorithm for managing battery groups and solar panels, such as an array consolidation and switching unit (ACSU).

The battery array **200**, whether composed of a single battery bank **224** or multiple battery banks **224**, offers a number of features and advantages. First, the battery array **200** stores electrical power for the electric loads **220**. By way of illustration, the solar-powered aircraft's **100** battery arrays **200** may provide, in aggregate, about 50 to 100 kWh in total energy storage to the solar-powered aircraft **100***a*, **100***b* when fully charged. As can be appreciated, however, the amount of energy storage can be increased or decreased by adjusting the number of battery pack assemblies **202** to achieve a desired amount of energy storage. Second, the battery array **200** supplies power through nighttime operation for at least a predetermined period of time (e.g., about 60 to 120 days, or about 90 days). Finally, the battery array **200** tolerates single-fault for flight safety such that the battery array **200** will operate normally in the event of a failure of a battery pack assembly **202**, a battery pack **212**, or battery cell **772** thereof. For example, the components of the battery array **200** can be provided as line replaceable units (LRU), where a defective battery cell **772** in the battery pack **212** can be switched offline (e.g., switched out/bypassed) to provide further fault protection. Similarly, a defective battery pack **212** in the battery pack assembly **202** can be switched offline to provide further fault protection. Each battery pack assembly **202** may contain, for example, six battery packs **212**. The battery packs **212** may be arranged in series, parallel, or a combination thereof to yield a self-reconfigurable multi-cell system (e.g., configured to supply between 130 VDC and 327 VDC). As will be discussion in connection with FIGS. **7***a* through **7***c*, the battery cells **772** of the battery pack **212** may be dynamically reconfigured to enable, inter alia, solar peak power tracking and discharge voltage regulation.

FIG. **3** illustrates a diagram of an example simplified single power channel **300** for the solar-powered aircraft **100***a*, **100***b*. As will be appreciated, the solar-powered aircraft **100***a*, **100***b* may use multiple simplified single power channels **300** (e.g., one per fuselage **110**, one per propulsor **124**, etc.). The ACSU **302** may be operably coupled to the battery array **200** (or portion thereof) and the solar panels **106** (or a solar array **226**). The ACSU **302** is used to distribute power with and/or between the battery array **200**, the solar panels **106**, and the electric loads **220** (e.g., the drive system **314**, avionics **312**, and any payloads). The drive system **314** generally comprises a motor controller **306**, one or more propulsors **124** (e.g., a propeller **124***a* coupled to a motor **124***b*), and output filtering **320**, which filters power delivered by the motor controller **306**. The output filtering **320** (e.g., one or more electronic filters) may be positioned between the motor controller **306** and the one or more propulsors **124**. The motor **124***b* may employ, for example, an ironless core Halbach array. A Halbach array employs an arrangement of permanent magnets that augments the magnetic field on one side of the array, while cancelling the field to near zero on the other side. This is achieved by having a spatially rotating pattern of magnetization.

The propeller **124***a* may employ variable pitch blades where the blades are configured to rotate about their long axis to change the blade pitch relative to the hub. In certain aspects, the propeller **124***a* may be configured as a reversible propeller where the pitch can be set to a negative value, thereby creating a reverse thrust. A reverse thrust can be used for, inter alia, braking without the need to change the direction of shaft revolution. An optimal pitch for the propeller blade during climb flight conditions can be selected as a function of the motor's **124***b* design or operating parameter. In certain aspects, the propeller blades may be pitched to maintain an amount of thrust while the RPM is decreased. For example, where the maximum velocity and minimum DC bus voltage define a motor voltage constant (KV), the ceiling climb velocity may be reduced from 1,100 to 1,000 revolutions per minute (RPM) to decrease velocity range and increase optimum DC bus voltage for cruise at altitude.

A motor controller **306** is an electronic circuit configured to vary a motor's speed, its direction, and, when desired, to act as a dynamic brake. The motor controller **306** is illustrated with a DC link **316** and a voltage-source inverter (VSI) converter **322**, where the rectifier comprises a diode-bridge and the DC link **316** is a shunt capacitor. The motor controller **306**, in effect, provides an electronically-generated three-phase electric power voltage source of energy for the motor **124***b*. In operation, the motor controller **306** provides an electronically-generated three-phase electric power voltage source of energy for the motor **124***b*. The pulse width modulation (PWM) frequency of the motor controller **306** may be optimized for combined motor **124***b* and motor controller **306** efficiency. For example, the PWM frequency may be optimized to lower control risk due to high rate of current change (dI/dt), which can be particularly useful in situations with large voltage overhead. Further, optimizing the PWM frequency can address bus capacitance for short and long lines and bus outage.

The voltage at which a solar panel **106** or a solar array **226** can produce maximum power is called the maximum power point (MPP, or, sometimes, peak power voltage). With reference to the current (A) and power (kW) graphs **400***a*, **400***b* of FIG. **4**, MPP tracking (MPPT) is used to extract a maximum available power from the solar panel **106** at the current conditions. MPPT is important in solar powered systems. Generally, MPPT varies solar panel load loading to optimize solar output power. The electrical connection between solar panel(s) **106** and battery array **200** (or portion thereof), in conjunction with dynamic reconfiguration of the battery array **200**, enables MPPT of the solar panel(s) **106** (e.g., at 2 Hz). For example, a perturb-and-observe algorithm may be applied as the MPPT control scheme. Perturb-and-observe techniques can be implemented by adding (or removing) a battery cell **772** to (or from) the battery pack **212**. Therefore, in operation, battery cells **772**, for example, can be added or removed from the battery string in battery pack **212** to facilitate MPPT. Generally, optimum voltage can be achieved within ½ cell voltage on average with only approximately ~0.7% error.

During daylight hours, each solar panel **106** may be connected to a battery bank **224**, whereby solar energy collected by the solar panels **106** is used to charge the battery bank(s) **224**. Solar panels **106** that are generating the highest power (e.g., the most power) may further be used to supply power to the drive system **314**, thereby maximizing usage of the generated power. As can be appreciated from the diagram, there is no power conversion loss between the solar panels **106** and battery bank **224**/electric loads **220**, aside from Joule loss attributable to, for example, wiring resistance and heating.

FIG. **5** illustrates a block diagram of an example electrical power system **500** for the solar-powered aircraft **100***a*, **100***b*. In operation, the electrical power system **500** provides power to the solar-powered aircraft **100***a*, **100***b* via a combination of battery arrays **200** and solar panels **106** (e.g., solar arrays **226**). While the following discussion and figures will use the term solar panel **106**, it should be understood that the disclosure is not necessarily limited to a single solar panel **106**, but could be a single solar panel **106** or multiple solar panels **106** arranged in a solar array **226**.

Power from the solar panel **106** and/or battery array **200** can be used to power, inter alia, avionics **312** (e.g., actuators, control systems, etc.), one or more payloads **504**, etc. For example, the power from the solar panel **106** and/or battery array **200** may be used to power, in response to commands from a flight controller or the vehicle management system **218**, one or more wing servos **308***a* (e.g., actuators to control the flight control surfaces on the wing **102**, if used, such as aileron) and tail servos **308***b* (e.g., actuators to control the flight control surfaces on the tail sections **112**, such as rudders **114** and elevators **116**). The battery arrays **200** and various servos (e.g., the wing servos **308***a* and the tail servos **308***b*) may be monitored by a line replaceable unit (LRU) **310**.

Each battery array **200** may include one or more battery pack assemblies **202**, which may be arranged into one or more battery banks **224**, each battery bank **224** being composed of two or more battery pack assemblies **202**. The battery banks **224**, for example, may be positioned on the fuselage **110**, tail sections **112**, the wing **102** (e.g., the leading edge or the upper surface), etc. Each propulsor **124** is illustrated as having a motor **124***b* and a dedicated motor controller **306**. Additional solar panels **106** may be positioned on each of the tail sections **112** (e.g., the horizontal stabilizer **126** and the vertical stabilizer **108**). In certain aspects, the wing **102** may support multiple solar panels **106** that are arranged into different, separate solar arrays **226**. For example, a first solar panel **106** may be positioned at the leading edge, while a second solar panel **106** may be positioned on an upper (top) surface of the wing **102**, between the leading edge and the trailing edges (e.g., forward of flight control surfaces, if used).

An advantage of the electrical power system's **500** architecture is that the power buses are nominally isolated from one another. For example, the electrical power system **500** may be generally divided into sub-systems **502***a*, **502***b*, **502***c* (e.g., electrically-isolated domains) such that electrical failure in one sub-system does not propagate to another sub-system. For example, the electrical power system **500** may be generally divided into two or more electrically isolated sub-systems (illustrated as three sub-systems **502***a*, **502***b*, **502***c* in FIG. **5**), each sub-system may correspond to a different region of the solar-powered aircraft **100***a*, **100***b* (e.g., a fuselage **110**, wing **102**, portion of a wing **102**, etc.). Accordingly, damage to components of the electrical power system **500** situated at one region of the solar-power aircraft

100*a*, **100***b* (e.g., a wing **102**) should not propagate to components of the electrical power system **500** situated at other regions of the solar-power aircraft **100***a*, **100***b* (e.g., the fuselages **110**, tail sections **112**, etc.). As illustrated, each sub-system **502***a*, **502***b*, **502***c* of the solar-powered aircraft **100***a*, **100***b* may include a solar panel **106** to collect energy, a battery bank **224** to store energy collected by the solar panel **106**, and a dedicated ACSU **302***a*, **302***b*, **302***c*.

While sub-systems **502***a*, **502***b*, **502***c* are self-sufficient to limit failure propagation, to further mitigate failures, cross-tie switches **304***a*, **304***b* can be positioned between sub-systems **502***a*, **502***b*, **502***c* to transfer power across the solar-powered aircraft **100***a*, **100***b*. Therefore, the ACSUs **302***a*, **302***c* of the first and third sub-systems **502***a*, **502***c* may couple to the ACSU **302***b* of the second sub-system **502***b* via a set of cross-tie switches **304***a*, **304***b*. In operation, the cross-tie switches **304***a*, **304***b* may be selectively actuated to couple, electrically and communicatively, the desired sub-systems **502***a*, **502***b*, **502***c*. For example, in the event of failure of the ACSU **302***c* of the third sub-system **502***c*, the cross-tie switch **304***b* may be actuated to allow the ACSU **302***b* of the second sub-system **502***b* to control the power components of the third sub-system **502***c* in lieu of the ACSU **302***c*. The cross-tie switches **304***a*, **304***b* may employ mechanical switches (e.g., solenoid-driven relays), solid-state switches (e.g., transistors, such as insulated-gate bipolar transistors (IGBT), field effects transistors (FETs), metal-oxide-semiconductor field-effect transistors (MOSFET), etc.), or a combination thereof. Each of the cross-tie switches **304***a*, **304***b* may be controlled by, for example, one or more of the ACSUs **302**.

FIG. **6** illustrates a power diagram **600** for an example ACSU **302**. The ACSU **302**, which is illustrated in the daytime configuration, provides flexibility in powering the motors **124***b* coupled to a local motor bus **324** from one or more sources. As illustrated, the ACSU **302** is coupled to one or more solar panels **106** and battery banks **224**, which may be positioned on the wing **102**, tail section **112**, etc. As illustrated, the battery banks **224** can be coupled to the local motor bus **324** through one or more of the ACSU **302** within the electrical power system **500**. The number of battery pack assemblies **202** or battery banks **224** in each battery array **200** may vary depending on the physical constraints of the installation location in the solar-powered aircraft **100***a*, **100***b*. For example, five battery pack assemblies **202** may be arranged in a battery bank **224** in each wing **102**, while two battery packs assemblies **202** may be may be arranged in a battery bank **224** of the leading edge of each wing **102** and/or the tail section **112**. The battery banks **224** may be coupled to the local motor bus **324** using one or more switches **328** as a function of, inter alia, the charge state of the battery array **200** and/or maximum power points (MPP) voltage of the solar panel **106**. The one or more switches **328** may be mechanical switches, solid-state switches, or a combination thereof. One or more electrical safety devices **326** (e.g., fuses, e-Fuses, circuit breakers, resettable fuses, such as a polymeric positive temperature coefficient (PPTC) devices, etc.) may be provided in-line between the local motor bus **324** and the motor controller **306** to provide over-current protection. While the solar panels **106** of FIG. **6** are illustrated as tied directly to a battery bank **224**, the avionics **312** and/or payload **504** may instead be configured to pull power from all battery banks **224** of the electrical power system **500**, which may be arranged in an "OR" configuration using, for example, ideal diodes.

Solar panels **106** can display different MPP voltages depending on the age and operating conditions of the solar-powered aircraft **100***a*, **100***b*. Operating conditions include, for example, shadowing, incident angle, etc. Therefore, the solar-powered aircraft's **100** solar panels **106** are distributed as solar arrays **226** on areas of the airframe that have similar solar incidence angles (displaying similar power point behavior). By separating the electrical power system **500** into multiple sub-systems **502***a*, **502***b*, **502***c*, each representing an array zone (e.g., an array zone for each of the fuselage, wing, leading edge, tail, etc.) and separately controlling the battery voltage in each zone, the MPP for each solar array **226** is achieved. The solar-powered aircraft **100***a*, **100***b* may have, for example, nine separate solar arrays **226**, each corresponding to a different array zones. The array zones can include, for each wing **102** (or portion thereof), a leading edge array, a wing (upper surface) array, and a tail array.

Due to their surface area, the wing(s) **102** is/are typically the largest overall contributor to energy collection. The solar panels **106** may employ thin-film copper indium gallium selenide (CIGS) for the bulk of the solar arrays, which offer efficiencies of about 12 to 17%. Thin-film CIGS arrays can be fabricated on a flexible substrate, which is useful for covering curved surfaces (e.g., aircraft wings). The flexible substrate may be, for example, a polyamide substrate. In another aspect, where desired, the solar panels **106** may employ thin-film gallium arsenide (GaAs) to target high-value locations on the solar-powered aircraft **100***a*, **100***b*, which offer efficiencies in excess of 25%. During testing, GaAs arrays have demonstrated un-encapsulated efficiencies of about 28% with a mass of 237 g/m^2, which is about 2.6 times the mass of the CIGS arrays.

Traditional, rechargeable battery packs contain a hard-wired string of batteries (a fixed battery string). A fixed battery string architecture can minimize the footprint (e.g., size, weight, power requirements, etc.) of the battery management system, but the output voltage has an increasing variance during a cycle from fully charged to fully discharged as the battery cell count increases and/or the battery cells cycle from fully charged to fully discharged. Therefore, as a result of the large output swing, additional hardware is typically implemented to regulate the output voltage of the battery system at a penalty of reduced overall efficiency lost to the output conversion process. A battery management system that can intelligently reconfigure the number of batteries (e.g., battery cells) in a battery string can obviate the need for an additional voltage regulator stage. Therefore, the battery array **200** may allow for dynamic reconfiguration at various levels of control granularity (e.g., per battery bank **224**, per battery pack assembly **202**, per battery pack **212**, and/or per battery cell **772**).

Battery pack assemblies **202** in each sub-system **502***a*, **502***b*, **502***c* or region of the solar-powered aircraft **100***a*, **100***b* may be partitioned into battery banks **224**. Each battery bank **224**, as noted above, is typically composed of two or more battery pack assemblies **202**. The quantity of battery pack assemblies **202** per battery bank **224** and the number of battery banks **224** per sub-system **502***a*, **502***b*, **502***c* may be sized based on the size of the local solar panel **106** (or solar array **226**) and contribution to overall energy collection. In one example, five battery pack assemblies **202** may be arranged to define the battery bank **224**. Each battery bank **224** may be matched to a solar panel **106** or solar array **226**. For example, (1) the solar panel **106** in the wing **102** may be paired with the battery bank **224** in the wing **102**, (2) the solar panel **106** in the leading edge of the wing **102** may be paired with the battery bank **224** in the leading edge of the wing **102**, and (3) the solar panel **106** in the tail section **112** may be paired with the battery bank **224** in the tail section **112**. The matching may be designed to minimize the effect upon the electrical power system **500** in the event of localized damaged to the solar-powered aircraft **100***a*, **100***b*.

The solar-powered aircraft **100***a*, **100***b* can include a battery management system **700** to regulate the output voltage of a multi series-connected reconfigurable battery system (e.g., battery pack assembly **202**), by dynamically selecting a subset of all available battery cells **772** and dynamically switching them in to (online) or out of (offline) the battery string **766** (aka, cell string or cell string array).

The battery management architecture provides an intelligent processing system that monitors and controls the reconfigurable battery functions. To that end, the battery management architecture includes a battery pack controller **730** operatively coupled to a battery supervisory circuit **732** to enable (online) or bypass (offline) any battery cell **772** in the battery string to adjust the variable output voltage of the reconfigurable battery pack **212** to achieve a commanded output voltage for the battery string. While illustrated using separate blocks and components, the battery pack controller **730** and the battery supervisory circuit **732** may share common circuitry and/or common processors. For example, the battery pack controller **730** and the battery supervisory circuit **732** may be provided as a single system or component.

As will be discussed, the battery management system **700** can use a combination of hardware switching and protection elements, and a software-based cell-selection process based on a number of cell- and pack-level criteria. The hardware instrumentation measures one or more parameters, including battery voltage, battery temperature, battery-string voltage, battery-pack voltage, battery-pack current, battery-pack-assembly voltage, battery-pack-assembly current, battery pressure (e.g., cell-stack pressure), and/or other parameters useful to inform the cell-selection process within the battery management system **700**. This information is evaluated by a processor and associated software via the battery pack controller **730** to determine the state of charge (SoC), state of health (SoH), and equivalent resistance of each battery cell **772** in the battery pack **212**, which may be updated on a periodic basis.

As noted above, battery management systems that cannot switch battery cells **772** in or out of a battery string **766** are limited by the weakest battery cell **772** in the battery string **766**. Such limitations include, for example, battery pack capacity, charge rate (enter balance charge early), and maximum discharge rate (high internal resistance). Using a battery pack controller **730** to implement a reconfigurable architecture via one or more battery switches **762** (e.g., a bi-directional switch) allows for the creation of any combination of battery cells **772** in a battery string **766**—up to the maximum number of battery cells **772** in the battery pack **212** of the battery pack assembly **202**. Additionally, the reconfigurable architecture provides the ability to regulate the output voltage of the battery pack assembly **202** to within 50% of a battery voltage. An obstacle, however, is that there will need to be excess battery cells **772** in the battery pack assembly **202** to recover from failures or regulate output voltages.

FIG. **7***a* illustrates a block diagram of an example battery management system **700** having battery pack assembly **202** in a reconfigurable architecture. The battery management system **700** provides a number of advantages. First, the battery management system **700** provides a modular architecture that can be modular down to the level of an individual battery cell **772**. Second, it provides a complete solution to reconfigurable battery protection and management. Third, it allows for the addition and removal of battery cells **772** from a series of a battery string **766**, which can be performed to adjust an output voltage to yield a variable output voltage or to bypass a defective battery cell **772**. Fourth, it enables isolated power domains (e.g., switchable battery modules **770**, battery packs **212**, battery pack controller **730**, etc.) to enable scalable configurations. Fifth, it offers output regulation without requiring complex voltage conversion circuitry. Finally, it can detect and remove battery cells **772** as they wear out or fail without diminishing overall performance of battery pack **212** or battery pack assembly **202**.

The battery pack assembly **202** generally comprises a battery pack controller **730** and a plurality of battery packs **212** (illustrated in FIG. **7***a* as six battery packs **212***a*, **212***b*, **212***c*, **212***d*, **212***e*, and **212***f*) connected to one another to define a battery pack string **774**, which can serve as a battery pack assembly **202**. In operation, the battery pack controller **730** monitors and controls operation of the battery pack string **774**, including each of the battery packs **212** and components thereof. The battery pack controller **730** may generate a plurality of system outputs (e.g., instructions, which may be analog or digital) to control operation of the battery pack assembly **202** and/or battery packs **212**. For example, the battery pack controller **730** can be configured to generate cell-select commands to insert/bypass individual battery cells within the battery packs **212**. The system outputs may be based on two or more system inputs. Example system inputs include, inter alia, individual voltage measurements (e.g., per battery cell **772**), individual temperature measurements (e.g., per battery cell **772**, which may be measured via temperature sensor **758**), current measurements (e.g., through battery string **766**), and output voltage measurements of the battery pack assembly **202** (e.g., the measure value of the variable output voltage), which may be measured on each side of the top switch **704**. Example system outputs may include, inter alia, battery switch control instructions (e.g., a signal/command), the power to the connected load (e.g., a per battery pack **212** or per battery pack assembly **202** basis), and total voltage (e.g., on a per battery pack **212** or per battery pack assembly **202** basis). In other words, the battery pack controller **730** selectively inserts/bypasses battery cells **772** so that they can be charged, discharged, or bypassed. For example, the battery cells **772** may be selectively bypassed to achieve a desired voltage or to charge/discharge only a select number of battery cells **772** (e.g., depending on the operating mode or conditions).

The battery pack controller **730** also provides over-voltage and under-voltage protection, as well as over-current protection and short-circuit protection. The battery pack assembly **202** may comprise, for example, six battery packs **212** (illustrated as **212***a* through **212***f*) electrically connected as a string in series; however, the quantity of battery packs **212** in the battery pack assembly **202** may be sized based on the energy storage needs of the application. It is also possible to electrically connect the battery packs **212** in other electrical configurations to achieve a desired voltage and/or capacity (e.g., in parallel, or a combination of series and parallel).

As illustrated, the battery pack controller **730** may comprise a plurality of bus output switches **768**, a microcontroller unit (MCU) **708** operatively coupled with a memory device (e.g., RAM, ROM, flash memory, etc.), a precision current sensor **726** to measure the current to/from the string of battery packs **212**, a set of input/output (I/O) expander integrated circuits (IC) **776***a*, **776***b*, and a DC power supply **728** (e.g., +3.3 VDC supply) to supply any power needed to operate the various components of the battery pack controller **730**, such as the processors (e.g., MCU **708**) and other ICs. Depending on the desired number of connections, the I/O expander ICs **776***a*, **776***b* may be, for example, a 16-bit expander.

The plurality of bus output switches **768** can be used to couple the battery pack string **774** to the ACSU **302** so that the battery pack string **774** (or portion thereof) can be charged or discharged. The plurality of bus output switches **768** may comprise, for example, a pre-charge switch **702**, a top switch **704** (e.g., a main switch), and an ideal diode switch **706**. Each of the bus output switches **768** may be arranged electrically in parallel. Voltage and current sensing of the battery bank **224** of the battery pack assembly **202** may be determined at the bus output switches **768**. The plurality of bus output switches may be mechanical switches, solid-state switches, or a combination thereof.

The pre-charge switch **702** may be a bi-directional, maximum string voltage blocking, high impedance output contactor. The pre-charge switch **702** electrically connects the plurality of battery packs **212** to the ACSU **302**. As illustrated, the pre-charge switch **702** is provided in line with one or more resistors to provide surge suppression and to limit charge current at the end of charge. The pre-charge switch **702** may employ a bidirectional blocking switch element rated to the maximum output of the battery pack assembly **202**. Bi-directionality allows the switch to control current flowing into or out of the battery pack assembly **202**. The pre-charge switch **702** may have a higher resistance relative to the top switch **704** (e.g., about 10 ohm (Ω) to 30Ω, or about 20Ω). In operation (i.e., when closed), the pre-charge switch **702** limits in-rush or out-rush currents during safe-to-mate bus connections.

The top switch **704** may be a bi-directional, maximum string voltage blocking, low impedance output contactor. The top switch **704** connects the plurality of battery packs **212** directly to the ACSU **302**. The top switch **704** may be designed with ultra-low resistance to minimize losses during nominal operation, resulting in a low insertion loss. The top switch **704** may employ a bidirectional blocking switch element rated to the maximum output of the battery pack assembly **202**. Bi-directionality allows the top switch **704** to control current flowing into or out of the battery pack assembly **202**. The top switch **704** enables the battery packs **212** (e.g., those of the switchable battery modules **770**) to use switches with lower blocking voltages.

The ideal diode switch **706** may be a unidirectional, maximum string voltage blocking, low impedance discharge only contactor. The ideal diode switch **706**, when enabled, prevents current flow into the plurality of battery packs **212** through top switch **704** via the diode. The ideal diode switch **706** allows only for discharging of the battery pack assembly **202**. The ideal diode switch **706** may be typically used when multiple battery pack assemblies **202** are connected in parallel (e.g., to define the battery bank **224**).

The MCU **708** controls overall operation of the battery pack assembly **202** in response to commands from, for example, the system controller **216**. For example, the MCU **708** may perform battery management and control algorithms to ensure that the battery cells **772** in the system are operating with in safe operating conditions. To that end, the MCU **708** may monitor, inter alia, SoC, SoH, and battery resistance, which can be used to perform sorting and battery balancing. The MCU **708** may be operably coupled with the ACSU **302** over, for example, a controller area network (CAN). The MCU **708** comprises a general purpose (digital) input/output (GPIO) signals, analog-to-digital converter (ADC) **710**, a set of CAN interfaces **712**, **714** and a plurality of serial peripheral interface (SPI) buses **716**, **718**, **720**, **722**, **724**. The MCU **708** is communicatively coupled with each of the battery packs **212** via one or more SPI data busses. I/O expander ICs **776***a*, **776***b* allow for multiple control signals that expand the available I/O to the MCU **708**.

FIG. **7***b* illustrates a block diagram of an example battery pack **212** (e.g., Detail B of FIG. **7***a*, battery pack **212***a*) having a battery supervisory circuit **732**. Together with the battery pack controller **730**, the battery supervisory circuit **732** converts cell-select commands from the battery pack controller **730** to selectively insert/bypass individual battery cells **772** of the battery string **766** within the battery pack **212**, while also conditioning and digitizing voltages and temperatures of the individual battery cells. A strain measurement may be included from each battery pack **212** to monitor the compression of the battery cells **772** of each battery pack **212**. The battery pack **212** generally comprises a plurality of battery cells **772**, and a plurality of battery switches **762** to selectively enable (activated) or bypass one or more of the plurality of battery cells **772** within the battery string **766**. The plurality of battery switches **762** may be electrically coupled to the plurality of battery cells **772** via a printed circuit board assembly (PCBA). The battery cells **772** may be provided as single-cell batteries, multi-cell batteries, or a combination thereof. Depending on the desired nominal voltage of a multi-cell battery, for example, the battery cells may be electrically arranged and connected in a series configuration, in a parallel configuration, or a combination thereof to achieve a desired nominal voltage and/or power for the battery cell **772**.

In addition to serving as a battery cell interface, the PCBA can serve as a platform for the battery supervisory circuit **732** (or a portion thereof). The battery supervisory circuit **732** generally comprises low voltage circuitry, high voltage circuitry, a plurality of temperature sensors **758**, and a plurality of strain sensors **760**. The battery pack **212** may comprise a dedicated memory **734** for storing battery cell **772** and PCBA-specific parameters.

A pair of quad-channel digital isolators **778***a*, **778***b* may be communicatively coupled with the I/O expander ICs **776***a*, **776***b* of the battery pack controller **730**. The pair of quad-channel digital isolators **778***a*, **778***b* may be used to communicate digital signals from the battery pack controller **730**, across a magnetic, optical, or galvanic isolation boundary between the low and high voltage circuitry, to the high voltage side of the circuitry.

An I/O expansion module **740** may be used to communicate data directionally between the battery pack controller **730** (via the quad-channel digital isolator **778***a*) and the battery string **766**. As illustrated, the battery string **766** generally comprises a plurality of switchable battery modules **770**, each switchable battery module **770** having a battery cell **772** and a battery switch **762** associated therewith. As will be described in greater detail below, the switchable battery modules **770** may be electrically arranged in series to define the battery string **766** composed of battery cells **772** that are configured in an active state (e.g., via the battery switches **762**).

The I/O expansion module **740** may communicate, for example, switch control signals between the battery pack controller **730** and the battery switches **762** of the switchable battery modules **770** to selectively activate/deactivate the battery cells **772**, for example. The I/O expansion module **740** may be, for example a 16-bit I/O expansion module (e.g., one for each of the 16 battery cells **772**). A dual channel isolator **748** may be positioned between the I/O expansion module **740** and each of the battery switches **762**. In the event of voltage loss at one or more any battery cells **772** voltage (resulting from, for example, a broken battery cell tab/contactor), an auxiliary (AUX) power supply (PS) **750** can be included at each battery pack **212** to ensure the local switching circuit remains powered through the voltage loss event. The auxiliary power supply has an isolated output, so it can be used at every cell location. The auxiliary power supply may also be enabled by the loss of the associated cell voltage.

An isolated power module **736** can be provided to supply power needed to operate the various components (e.g., ICs, such as the memory **734**) of the low and high voltages circuits. The isolated power module **736** may be coupled to a reference voltage **738** (e.g., +3.3V), +3.3 VDC (DIG), +5.7 VDC (ANA). The isolated power module **736** may be, for example, an isolated flyback μModule DC/DC converter with low-dropout (LDO) post regulator with an isolation rating of, for example, 725 VDC. The isolated power module **736** may be operable over an input voltage range of 3.1V to 32V with an output voltage range of 2.5V to 13V (set by a single resistor). The isolated power module **736** may also include a linear post regulator whose output voltage is adjustable from 1.2V to 12V as set by a single resistor. A suitable isolated power module **736** includes, for example, the LTM8048, which is available from Linear Technology.

Various parameters of the battery cells **772** may be measured and communicated to the battery pack controller **730** (via the battery supervisory circuit **732**) for processing. The parameters may be monitored/measured on a per battery cell **772** basis. Example parameters include, for example, voltage, current, temperature, and compression of the battery cell **772**. For example, the plurality of temperature sensors **758** and the plurality of strain sensors **760** can be physically positioned adjacent the battery cell **772** in the battery pack **212** to monitor, respectively, the temperature and strain of each of the battery cells **772**. For example, each battery cell **772** may be associated with a temperature sensor **758** and/or a strain sensor **760** to allow the battery supervisory circuit **732** to monitor each of the battery cells **772** individually. In certain aspects, the battery cell **772** may be configured as a 2p cell assembly where a temperature sensor **758** and/or a strain sensor **760** may be positioned between the two p cells. Alternatively, a single strain sensor **760** could be used to monitor the compression of the full battery pack **212**.

Measurements from each of the plurality of temperature sensors **758** (e.g., cell temperature) can be communicated to a thermistor conditioning amplifier **754** on the high voltage side, while measurements from the strain sensor(s) **760** (e.g., cell compression) can be communicated to a strain signal amplifier **756** on the high voltage side. The voltage measurements for each battery cell **772** may be provided using a differential amplifier **752**, which can function as a voltage sensor, on the high voltage side. In certain aspects, a thermistor conditioning amplifier **754** may be provided for each temperature sensor **758** and a differential amplifier **752** may be provided for each battery cell **772**. Therefore, in a battery pack **212** having 16 battery cells **772**, 16 thermistor conditioning amplifiers **754** and 16 differential amplifiers **752** may be used. While it is possible to provide a temperature sensor **758** and/or a strain sensor **760** at each battery cell **772**, a single temperature sensor **758** and/or a single strain sensor **760** may instead be used for the entire battery cell-stack of a battery pack **212**.

The measured parameters from the thermistor conditioning amplifiers **754**, the strain signal amplifier(s) **756**, and the differential amplifiers **752** may be inputted to one or more multiplexers. In operation, the one or more multiplexers select one of plurality of analog (or digital, if applicable) input signals from the various sensors and forwards the selected input into a single output. The one or more multiplexers may include, for example, a 2:1 multiplexer **744** and a 4:1 multiplexer **746**. The output from the 2:1 multiplexer **744** and the 4:1 multiplexer **746** may be inputted to an analog-to-digital (A-D) voltage converter **742**. The A-D voltage converter **742** may be, for example, a 16-channel (8-differential) micropower 16-bit ΔΣ analog-to-digital converter. The parameters, now in digital format, may be outputted from the A-D voltage converter **742** and back to the battery pack controller **730** via the quad-channel digital isolator(s) **778*a***, **778*b*** and SPI bus for processing. As can be appreciated, one or more clock (clk) signals may be used to synchronize the components during data/signal processing.

FIG. **7*c*** illustrates a diagram of an example battery string **766** for use in a battery pack **212**. As illustrated, the battery string **766** may comprise a plurality of switchable battery modules **770** arranged in series. Each switchable battery module **770** comprises, for example, a battery cell **772** (e.g., a single battery cell or multiple battery cells, which can be arranged as a cell assembly), a battery switch **762**, and a cell selection algorithm function **764**. For illustrative purposes, the battery string **766** is illustrated with six switchable battery modules **770**; however, additional or fewer switchable battery modules **770** may be used. In operation, one or more desired battery cells **772** can be selected and switched into the battery string **766** via the battery switches **762** such that aggregate string voltage of the battery pack **212** (output voltage) achieves a predetermined target output voltage.

The number of cells per battery cell **772** in a switchable battery module **770** may be adjusted based on the desired level of control granularity of the battery pack **212**. In one example (e.g., where a more-granular switching approach is desired), the switchable battery module **770** may comprise a single-cell battery with a single battery cell such that a single battery cell may be added to, or removed from, the battery string **766** one-by-one (i.e., individually). In other words, each battery switch **762** (and associated cell selection algorithm function **764**) may be associated with a single battery cell and configured to electrically connect (insert or activate) or electrically disconnect (remove or bypass) the single battery cell from the active battery string **766**.

In another example (e.g., where a less-granular switching approach is desired or acceptable), the switchable battery module **770** may comprise a multi-cell battery having multiple battery cells (e.g., two or more, which may be connected electrically to one another in series or in parallel) may be added to, or removed from, the battery string **766** individually. In such an arrangement, the group of battery cells within the battery pack **212** may be associated with a single cell selection algorithm function **764** and a single battery switch **762** such that the battery switch **762** can be selectively actuated to electrically connect or electrically disconnect the group of battery cells from the active battery string **766**. Therefore, the number of battery cells to be inserted or bypassed at a time using a single battery switch **762** may be selected based on the needs of the battery system.

In embedded designs, an A-D voltage converter **742** of the battery supervisory circuit **732** at each switchable battery module **770** (e.g., at the one or more battery cells) can serve as the voltage sensor to measure the voltage of the battery cells **772**.

Detail C provides an enlargement of an example battery switch **762**. The battery switch **762** may provide single pole, double throw (SPDT) switch functionality. Therefore, as illustrated, the battery switch **762** may be a SPDT switch where the pole (**1**P) can be connected to either the first throw (1T) to bypass the battery cell **772** (shunt switch position **762***a*) from the battery string **766** or the second throw (2T) to insert/activate the battery cell **772** (series switch position **762***b*) by including it in series with the battery string **766**. Each of the plurality of battery switches **762** can use low voltage MOSFETs with low series resistance to improve efficiency, which can be provided in small packages. The battery switch **762** can be implemented with MOSFET, mechanical relays, reed switches, or IGBT switches (or another form of solid-state switch) in a break-before-make (BBM or non-shorting) arrangement, which interrupts one circuit before closing the other, thereby mitigating any risk of shorting the battery cell **772** being switched. For example, the battery switch **762** may be provided using back-to-back FETs (e.g., N-MOSFETS) in common source configuration, TRIACs (a three terminal semiconductor device), bipolar junction transistors (BJT), etc.

Therefore, in one aspect, a reconfigurable battery system, such as the battery pack **212**, may include a plurality of switchable battery modules **770**, a battery supervisory circuit **732**, and a battery pack controller **730**. The plurality of switchable battery modules **770** are electrically arranged in series to define a battery string **766** defining an output voltage for the battery pack **212** (e.g., a variable output voltage), each of the plurality of switchable battery modules **770** comprising a battery (e.g., a battery cell **772**) and a battery switch **762**. Configuring the battery switch **762** in the first position (e.g., series switch position **762***b*) electrically places the battery in series with the battery string **766** to increase the output voltage, while configuring the battery switch **762** in the second position (e.g., shunt switch position **762***a*) electrically bypasses the battery from the battery string **766**. The battery supervisory circuit **732** is operably coupled to each of the plurality of switchable battery modules **770**, wherein the battery supervisory circuit **732** is configured to monitor, for each of the plurality of switchable battery modules **770**, one or more parameters of the battery. The battery pack controller **730** operably coupled to the battery supervisory circuit **732** to selectively switch, for each of the plurality of switchable battery modules **770**, the battery switch **762** between the first position and the second position based at least in part on the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage.

Using the example illustrated in FIG. **7***c*, certain battery cells **772** may be selectively bypassed based on, for example, their charge state to provide a desired string voltage. For example, if a string voltage of at least 10 volts is needed (a predetermined target output voltage), switchable battery modules **770** 1, 3, and 4 may be activated to provide 10.29 volts (i.e., 3.43 v+3.19 v+3.67 v), while the remainder are bypassed. As the voltages of the battery cells **772** of first, third, and fourth switchable battery modules **770** (1, 3, and 4) decrease during the discharge cycle (or increase during a charge cycle), one or more of the second, fifth, and sixth switchable battery modules **770** (2, 5, and 6) may be selectively activated or deactivate (e.g., one by one) to maintain a string voltage of at least 10 volts. Alternatively, a different group of switchable battery modules **770** may be activated to maintain the predetermined target output voltage. Therefore, the battery pack controller **730** may be configured to switch the battery switch **762** of each of the plurality of switchable battery modules **770** individually (i.e., one-by-one) until the predetermined target output voltage is achieved at the variable voltage output.

A battery pack **212** for the solar-powered aircraft **100***a*, **100***b* may comprise, for example, a battery string **766** with 32 battery cells **772**, which may be prismatic, cylindrical, or pouch cells. Therefore, as illustrated, each switchable battery module **770** within the battery pack **212** may employ a cell selection algorithm function **764** and a battery switch **762** to electrically connect or electrically disconnect (bypass) a battery cell **772** from the active battery string **766**, thereby adjusting the voltage of the battery string **766** one battery cell **772** at a time. Nominally, about 75% of the battery cells **772** may be active across the battery pack **212** at a given time, where fewer battery cells **772** are active at start of discharge because voltage of the battery cells **772** are higher at that time. As can be appreciated, as the voltage of the battery cells **772** decreases toward the end of discharge, additional battery cells **772** are needed to maintain the programmed voltage. Therefore, the battery pack **212** can be configured and sized such that all available energy is utilized at worst case (longest night) time of year.

All battery pack assemblies **202** in a single battery bank **224** can be programmed simultaneously. To achieve the high bus voltages, each battery pack assembly **202** may employ at least about 100 battery cells **772** and provided a usable voltage of about 2.75V to 4.3V per battery cell **772**. Battery pack assemblies **202** of more than 100 battery cells **772** in series are also contemplated for added capacity. Therefore, the battery pack assemblies **202** for the solar-powered aircraft **100***a*, **100***b* may comprise, for example, 10 to 1,000 battery cells **772**, more preferably about 50 to 500 battery cells **772**, even more preferably, about 75 to 300 battery cells **772**, most preferably, about 100 to 200 battery cells **772**. The bus voltage can be set dynamically in response to varying mission and aircraft conditions. For example, the bus voltage of the external bus can be reduced to increase drive system efficiency for night time and low altitude flight, to compensate for line drop when powering remote motors (via boom cross-tie switch(es) **304***a*, **304***b*) in the event of motor failure, or to implement MPPT.

The internal reconfiguration of the battery cell **772**, via the battery supervisory circuit **732** in the battery pack **212**, provides: (1) adjustable bus voltage during charge and discharge; (2) tolerance to battery cell failures; (3) lossless cell balancing during charge and discharge; (4) extended latitude reach or life through rest period; and (5) more accurate battery state estimation. For example, the battery pack **212** may employ a plurality of battery switches **762** to provide controlled access to individual battery cells **772** in the battery pack's **212** battery string **766**. Generally, the number of active ("online") battery cells **772** is greater than (or equal to) the maximum bus voltage, divided by the minimum voltage of the battery cells **772**. Using this approach, only a subset of battery cells **772** are charged or discharged at a given time, while the other cells are disconnected/rested (bypassed).

Traditional battery packs are vulnerable to even a single battery-cell failure, rendering the battery pack unusable and forfeiting the remaining energy still in the viable (i.e., good/usable) batteries. A programmable voltage architecture, however, provides the ability to bypass a defective battery cell **772** in the battery string **766** in accordance with a predetermined switching routine, thereby resulting in a battery pack **212** that is immune to battery and battery cell failures. Even multi-battery and multi-cell failures do not render the battery string **766** unusable and do not degrade battery pack capacity (except for the availability of the lost battery cells **772** that may be bypassed) until failure count of battery cells **772** accounts for a significant percentage of the total battery count. Such architecture allows for full utilization of the capacity of all viable battery cells in the battery pack **212**.

In addition to cell failure, as battery cells age over time (and multiple charge/discharge cycles), the impedance/resistance, and capacity degrade and battery cell characteristics diverge. Premature degradation of even a single battery cell can bring down a traditional pack, resulting in wasted energy trapped in remaining good cells. The battery supervisory circuit **732**, however, tracks impedance/resistance and capacity of each battery cell **772** over time. Accordingly, the battery pack **212** can implement preventive measures against cell degradation (or further cell degradation) by balancing the loading across the most viable battery cells. This implementation ensures that, absent an unexpected failure or defect, battery cells are constantly balanced and degrade at equal rate. The battery supervisory circuit **732** can therefore maximizes the capacity of the battery pack **212** (and therefore, the battery pack assembly **202**/battery bank **224**) over its expected/usable lifetime without dissipating excessive energy in battery cell balancing schemes. Accordingly, all available charge is used, but distributed over a larger population of battery cells.

When the battery cell **772** is out of the battery string **766** (i.e., bypassed), the battery's **772** SoC can be determined by measuring the battery's **772** open circuit voltage (OCV). When the battery cell **772** is in the battery string **766**, the battery's **772** SoC can be estimated by measuring the in-and-out-flowing current. One technique for estimating the SoC of a battery cell **772** using the in-and-out-flowing current is known as the coulomb counting method (also known as ampere hour counting and current integration). The coulomb counting method employs battery current readings mathematically integrated over the usage period to calculate SoC values, which can be given by the equation:

$$SoC = SoC(t_0) + \frac{1}{C_{rated}} \int_{t_0}^{t_0+\tau} (I_b - I_{loss})\,dt$$

where $SoC(t_0)$ is the initial SoC, C_{rated} is the rated capacity, I_b is the battery current, and I_{loss} is the current consumed by the loss reactions. The coulomb counting method then calculates the remaining capacity simply by accumulating the charge transferred in or out of the battery.

When a bypassed battery cell **772** is selected and switched into the battery string **766**, its internal impedance/resistance can be inferred by measuring the initial drop in cell voltage from the open-circuit (bypassed) to the closed-circuit (enabled or active) condition. Tracking the impedance/resistance of the battery cell **772** over time can be used as part of the SoH estimation to predict when a battery cell **772** is failing at a higher rate than other battery cells **772** in the battery string **766**. Battery cell **772** with a higher rate of increasing impedance/resistance could be selected for use less frequently than healthier battery cells **772** (those with lower impedance/resistance) to allow all battery cells **772** to degrade at approximately the same rate and maximize usable lifetime of the complete battery string **766**.

FIG. **8** illustrates an example architecture **800** for each of the plurality of switchable battery modules **770**. As illustrated, a switchable battery modules **770*n*** is positioned in series with adjacent switchable battery modules **770** (e.g., between the prior module **700*n*−1** and the next module **700*n*+1** in the series). The cell selection algorithm function **764** is configured to detect an over-voltage condition and/or an under-voltage condition, which may be used to provide both over-voltage and under-voltage protection to the battery cell **772**. For over-voltage protection of battery cell **772**, an output from the cell selection algorithm function **764** may be used to trigger a switch to introduce electrically a resistor to remove (e.g., dissipate) unwanted/excessive energy from battery cell **772**. To provide under-voltage protection of battery cell **772**, an output from the cell selection algorithm function **764** may be used as a trigger to override a battery switch signal from the switch controller **808** (e.g., the battery pack controller **730** via the battery supervisory circuit **732**).

During charge and discharge, the over-current protection function **804** protects the battery cell **772** from over-current conditions that would damage the battery cell **772**. The over-current protection function **804** may employ, for example, one or more electrical safety devices, including, inter alia, fuses, e-Fuses, circuit breakers, resettable fuses, such as a polymeric positive temperature coefficient (PPTC) devices, etc. The over-current protection mechanism could be resettable by the MCU **708** to check if the condition causing the fault has cleared.

The switch control **808** may be isolated to provide digital control of the battery switch's **762** state (e.g., via break-before-make (BBM) switch logic **810**). As battery cells **772** are switched into or out of the battery string **766**, the reference potential points for the switch control signals can vary up to the full string output potential. Isolation allows the high-voltage output side of the control signals to float with respect to one another, but the input side can have a single reference point shared by the MCU **708**. This maintains the correct commanded switch state for each switchable battery modules **770** (series or bypass/shunt). As noted above in connection with FIG. **7*b***, the switch control **808** may be isolated using an isolator, which may employ an opto-coupler (aka, an opto-isolator, photocoupler, or optical isolator), capacitive coupling, inductive coupling, magnetic coupling, etc.

The circuit and components thereof are normally powered by its local battery (e.g., battery cell **772**), which allows the battery string **766** to function. An auxiliary isolated power source **812** (e.g., AUX PS **750** or another power source), however, may be operatively coupled to the battery switch **762** to maintain the battery switch **762** in the shunt switch position **762*a*** so that the battery cell **772** is bypassed (shunted/removed) from the battery string **766** (or maintaining the battery switch **762** in the shunt switch position **762*a***) when an open battery terminal condition occurs (such as a broken cell tab or overly discharged cell). This condition is enabled when the voltage of the battery cell **772** is below a minimum operating voltage, which will enable the auxiliary power circuit. The output of the isolated power source **812** may be connected to the battery switch **762** via a blocking diode **806** to provide a diode-OR gate to switch the logic power source from either the local battery cell **772** or the auxiliary isolated power source **812** (whichever voltage is higher, for example). The auxiliary isolated power source **812** may include, for example, a DC-DC converter with transformer or capacitive isolation, or another battery. For a series connection, the battery switch **762** can operate as a high-side switch to assume the series switch position **762*b***, where the switch element is wired between the voltage source and load. For bypass (shunt) connections, the battery switch **762** operate as low-side switch to assume the shunt switch position **762***a* where the switch element is wired between the load and the negative reference point of the battery cell **772**.

As noted above, the battery switch **762** can be implemented in a break-before-make (BBM) arrangement. To that end, BBM switch logic **810** may be employed as it enables a single control line from the switch control **808** to switch the state of the battery cell **772** (between series and shunt) in the battery string **766** without risk of accidentally short circuiting the battery cell **772** by closing both switches simultaneously (i.e., simultaneously assuming both shunt switch position **762***a* and series switch position **762***b*).

The battery-voltage sensor **802** measures the voltage across the terminals (T**1**, T**2**) of the battery cell **772**. The battery-voltage sensor **802** may be provided using a differential amplifier (e.g., differential amplifier **752**), resistor divider, isolated amplifier, etc. The temperature sensor **758** may be positioned proximate the surface of the battery cell **772** to provide cell-temperature readings. The temperature sensor **758** may be, for example, a thermistor, thermocouple, diode, thermopile (infra-red), bolometer, etc.

The plurality of switchable battery modules **770** can be grouped (whether in series, as illustrated, in parallel, or a combination thereof) to provide or define a battery pack **212**. Multiple battery packs **212** can be connected in series (or, if desired, in parallel or a combination thereof) to form a battery pack assembly **202**, which may be arranged in battery banks **224** to define a battery array **200**. The control signals of the battery packs **212** are electrically isolated from other battery packs **212**. A battery supervisory circuit **732** (e.g., using an A-D voltage converter **742**) located on battery packs **212** can be used to read (1) the battery-voltage sensor **802** for each battery cell **772** in the battery pack **212** and (2) the temperature sensor **758** for each battery cell **772** in the battery pack **212**. The battery supervisory circuit **732** controls the battery switch **762** to switch an individual battery cell **772** into or out of the output battery string **766**. The battery supervisory circuit **732** interfaces with switching module of the battery pack controller **730** via the isolated switch control. The battery supervisory circuit **732** can also sense the series current through the battery string **766**, which, in combination with battery voltage and temperature, allows for tracking of battery metrics such as state of health, energy, power, charge, etc. The battery supervisory circuit **732** also protects the battery pack **212** from potentially dangerous conditions for the batteries connected in series string, such as over- or under-voltage, over- or under-temperature, or overcurrent.

While the various solar and battery power systems and methods are generally described in connection with a solar-powered aircraft, they may be applied to virtually any industry where a reconfigurable battery system is desired. In addition, the order or presentation of method steps is not intended to require this order of performing the recited steps unless a particular order is expressly required or otherwise clear from the context. Thus, while particular embodiments have been shown and described, it will be apparent to those skilled in the art that various changes and modifications in form and details may be made therein without departing from the spirit and scope of this disclosure and are intended to form a part of the invention as defined by the following claims, which are to be interpreted in the broadest sense allowable by law. It will be appreciated that the methods and systems described above are set forth by way of example and not of limitation. Numerous variations, additions, omissions, and other modifications will be apparent to one of ordinary skill in the art.

What is claimed is:

1. A method for reconfiguring a battery system having a battery pack controller operably coupled to a plurality of switchable battery modules that are electrically arranged in series to define a battery string defining an output voltage, each of the plurality of switchable battery modules comprising a battery and a battery switch associated therewith, each battery switch configured to selectively connect its battery to the battery string when in a first position and to bypass its battery when in a second position, the method comprising:

monitoring, for each of the plurality of switchable battery modules, one or more parameters of the battery via a battery supervisory circuit; and

selectively switching, for each of the plurality of switchable battery modules, the battery switch between a first position and a second position via the battery pack controller as a function of the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage, wherein the battery pack controller is configured to control the plurality of switchable battery modules based at least in part on instructions received from a solar array consolidation and switching unit (ACSU).

2. The method of claim **1**, wherein the one or more parameters include a voltage for the battery of each of the plurality of switchable battery modules.

3. The method of claim **1**, further comprising the step of maintaining the battery switch in the second position via an auxiliary isolated power source when an open battery terminal condition occurs.

4. The method of claim **3**, further comprising the step of preventing back-feeding of current into the auxiliary isolated power source via a blocking diode.

5. The method of claim **1**, further comprising the step of using a comparator to provide, for each of the plurality of switchable battery modules, voltage protection to the battery.

6. The method of claim **5**, further comprising the step of using the comparator to provide, for each of the plurality of switchable battery modules, both over-voltage protection and under-voltage protection to the battery.

7. The method of claim **6**, further comprising the step of overriding a battery switch signal from the battery pack controller in an under-voltage condition.

8. A reconfigurable battery system comprising:

a plurality of switchable battery modules electrically arranged in series to define a battery string defining an output voltage, each of the plurality of switchable battery modules comprising a battery and a battery switch,

wherein configuring the battery switch in a first position electrically places the battery in series with the battery string to increase the output voltage, and

wherein configuring the battery switch in a second position electrically bypasses the battery from the battery string;

a battery supervisory circuit operably coupled to each of the plurality of switchable battery modules, wherein the battery supervisory circuit is configured to monitor, for each of the plurality of switchable battery modules, one or more parameters of the battery; and a battery pack controller operably coupled to the battery supervisory circuit to selectively switch, for each of the plurality of switchable battery modules, the battery switch between the first position and the second position based at least in part on the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage, wherein the battery pack controller is configured to control the plurality of switchable battery modules based on at least in part on instructions received from a solar array consolidation and switching unit (ACSU).

9. The reconfigurable battery system of claim **8**, wherein the one or more parameters include a voltage for each battery.

10. The reconfigurable battery system of claim **9**, wherein the one or more parameters further includes a measured current passing through the battery string.

11. The reconfigurable battery system of claim **8**, wherein the plurality of switchable battery modules are arranged into a battery pack that is electrically arranged in series with a second battery pack to define a battery pack assembly.

12. The reconfigurable battery system of claim **11**, wherein the battery pack assembly is operably coupled to a second battery pack assembly in a parallel electrical arrangement to define a battery bank.

13. The reconfigurable battery system of claim **8**, wherein each of the plurality of switchable battery modules further comprises an auxiliary isolated power source to maintain the battery switch in the second position when an open battery terminal condition occurs.

14. The reconfigurable battery system of claim **13**, wherein the auxiliary isolated power source is operatively coupled to the battery switch via a blocking diode to prevent back-feeding into the auxiliary isolated power source.

15. The reconfigurable battery system of claim **8**, further comprising, for each of the plurality of switchable battery modules, a comparator to provide voltage protection to the battery.

16. The reconfigurable battery system of claim **15**, wherein the comparator is configured to provide, for each of the plurality of switchable battery modules, both over-voltage and under-voltage protection to the battery.

17. The reconfigurable battery system of claim **16**, wherein the reconfigurable battery system is configured to override a battery switch signal from the battery pack controller in an under-voltage condition.

18. The reconfigurable battery system of claim **8**, wherein, for each of the plurality of switchable battery modules, an isolator is positioned between the between the battery switch and the battery pack controller.

19. A reconfigurable battery system comprising:

a plurality of switchable battery modules electrically arranged in series to define a battery string defining an output voltage, each of the plurality of switchable battery modules comprising a battery, a battery switch, and an auxiliary isolated power source,

wherein configuring the battery switch in a first position electrically places the battery in series with the battery string to increase the output voltage,

wherein configuring the battery switch in a second position electrically bypasses the battery from the battery string, and

wherein the auxiliary isolated power source is configured to maintain the battery switch in the second position when an open battery terminal condition occurs;

a battery supervisory circuit operably coupled to each of the plurality of switchable battery modules, wherein the battery supervisory circuit is configured to monitor, for each of the plurality of switchable battery modules, one or more parameters of the battery; and

a battery pack controller operably coupled to the battery supervisory circuit to selectively switch, for each of the plurality of switchable battery modules, the battery switch between the first position and the second position based at least in part on the one or more parameters of the battery and in accordance with a predetermined switching routine such that the output voltage is substantially equal to a predetermined target output voltage.

20. The reconfigurable battery system of claim **19**, further comprising, for each of the plurality of switchable battery modules, a comparator to provide voltage protection to the battery, wherein the comparator is configured to provide, for each of the plurality of switchable battery modules, both over-voltage and under-voltage protection to the battery.

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